2-4 A Forecast Tool Using Java Script for Predicting Arrival Time of Interplanetary Disturbances to the Earth

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In this report, we presented a forecast tool to predict arrival time of interplanetary disturbances using a simple model and evaluation of this tool. The tool was written in Java script and arrival time of disturbances was calculated on web. Input parameters of this tool are occurrence time and initial speed of solar source of disturbance and background solar wind speed.

Keywords
Interplanetary disturbance, Java script, Solar wind, Coronal mass ejection

1 Introduction

In a famous episode in 1859, a major geomagnetic storm was observed on the Earth approximately thirteen hours after the British astronomer R.C. Carrington observed the occurrence of a white-light flare on the solar surface. From the latter half of the 1960s to the 1970s, disturbances in the solar corona referred to as coronal mass ejections (CMEs) were observed from space for the first time, via coronagraph observation; it was subsequently surmised that these CMEs were directly associated with geomagnetic storms [1]-[4]. However, even today, our forecasting of the occurrence of geomagnetic storms is only qualitative; we can only say for sure that a geomagnetic disturbance is induced by the arrival at the Earth of a disturbance that originated in the Sun. In order to conduct more effective "space weather forecasting," we must advance from this qualitative forecasting to quantitative forecasting. In terms of forecasting geomagnetic storms, it is necessary to predict precisely when a geomagnetic storm will occur, how large it will be, and how long it will last.

There have been several studies on forecasting the arrival time of solar disturbances at the Earth, and they have utilized empirical equations based on observation, simple models, and numerical simulations. An example of a model used in such studies is the shock-time-of-arrival (STOA) model[5][6], which assumes that an interplanetary shock propagates explosively, much like a supernova explosion, and predicts the shock arrival time at the Earth using the velocity of the disturbance within the corona determined from observation of type II solar radio bursts. Gopalswamy et al.[7] have presented an empirical equation for calculating the propagation time using the velocity and acceleration of CME derived from observation data of the LASCO (Large Scale Spectrometric Coronagraph) aboard the SOHO spacecraft, but their prediction error remains significantly large. The Hakamada-Akasofu-Fry (HAF) model developed by Hakamada, Akasofu, and Fry[8][9][10][11] uses a kinematic model to predict the propagation of the interplanetary disturbance. Dryer and Smith et al.[12] [13] [14] proposed a magnetohydrodynamic (MHD) simulation model called the interplanetary shock propagation model (ISPM), and have predicted arrival times using several input parameters: the velocity of disturbance (based on observation of type II solar radio bursts), the duration of flare (observed by the GOES satellite), and the location of flare occurrence on the Sun. They have also attempted to evaluate their model by comparing their results to actual observations. However, we have not yet reached the stage where we can declare the establishment of full-scale numerical prediction.

This report presents a tool, created with Java script, designed to predict the arrival time at the Earth of disturbances, using a simple model that can be used on the web. The results of evaluation of the precision of prediction using this tool are also reported. Finally, a tool has also been developed to determine the time of occurrence and the initial velocity at the Sun of a geomagnetic disturbance-inducing phenomenon based on the observed speed and time of arrival at 1 AU; this tool is also described in this paper.

2 The Model

Fig.1 presents the model on which our tool is based. The disturbance retains its initial velocity of V_0 to a distance of R_1 from the Sun, and from that point on, it decelerates with velocity inversely proportional to the power α of distance. The background solar wind was assumed to have a constant velocity of V_b. The velocity V of the disturbance at distance R from the Sun can thus be expressed by the following equations.

$$V = V_o + V_b \quad (R \leqq R_1) \qquad (1)$$

$$V = V_o (R_1/R)^{\alpha} + V_b \quad (R > R_1) \qquad (2)$$

The values of R_1 and α are difficult to determine from direct observation, and so it was assumed here that a disturbance retains its initial velocity to 0.3 AU, after which its velocity decreases in inverse proportion to the 0.5 th power of distance (R_1 = 0.3 AU, α = 0.5). This assumption was based on observation by the SOHO/LASCO that fast CMEs that are decelerated in interplanetary space are not normally decelerated within the field-of-view of the LASCO (30 solar radii)[15]. Helios satellite observations of the interplanetary space between 0.3 AU and 1 AU have revealed that sock deceleration is inversely proportional to the 0.5th power of distance[16][17].

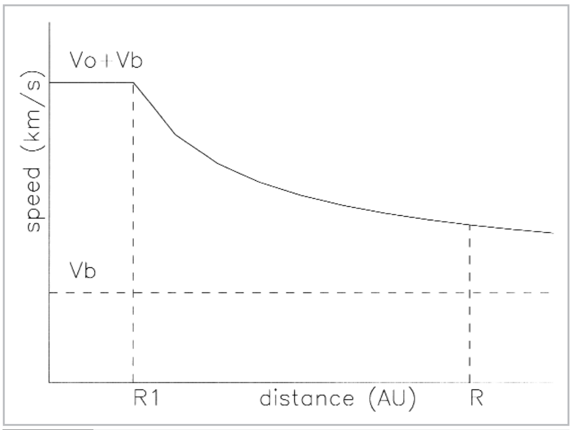

Fig.1 *Assumed velocity change of disturbance*

$$V = V_o + V_b \quad (R \leqq 0.3\text{AU}) \qquad (3)$$

$$V = V_o (R_1/R)^{0.5} + V_b \quad (R > 0.3\text{AU}) \qquad (4)$$

If R_2 is the distance from the Sun to the Earth, then the propagation time T of the disturbance from the Sun to the Earth will be:

$$T = \int_{R_0}^{R_1} \frac{dR}{V} + \int_{R_1}^{R} \frac{dR}{V} \qquad (5)$$

$$= \frac{R_1 - R_s}{V_o + V_b} + \frac{R - R_1}{V_o} + 2V_s \frac{R_1 - \sqrt{RR_1}}{V_o^2}$$

$$+ 2R_1 \frac{V_s^2}{V_o^3} \cdot \log \frac{V_o \sqrt{R/R_1} + V_s}{V_o + V_s}$$

The arrival time at the Earth of a solar event that induces a disturbance can be calculated by adding the propagation time given by Eq.(5) to the time of occurrence of the event at the Sun. Furthermore, the velocity of the disturbance near the Earth can be predicted from Eq.(4). Conversely, if the near-Earth velocity of the disturbance and the background solar wind velocity are given, then the initial velocity of the disturbance can be calculated from Eq.(4). Using this initial velocity, the propagation time can be calculated from Eq.(5), which can then be subtracted from the arrival time of the disturbance at the Earth to estimate the time of occurrence of the solar event associated with the disturbance.

Fig.2 and 3 show the graphical user interface (GUI) of the tool for calculating the above using Java script on the web. The tool in Fig.2 outputs the predicted arrival time and the velocity of the disturbance at 1 AU based on several input values: time of occurrence of the disturbance on the Sun, initial velocity of the disturbance, and background solar wind velocity. On the other hand, the tool in Fig.3 calculates the predicted values of the time of occurrence and initial velocity of the disturbance on the Sun when the parameters are input for the time of observation at 1 AU, velocity of disturbance at 1 AU, and the background solar wind velocity.

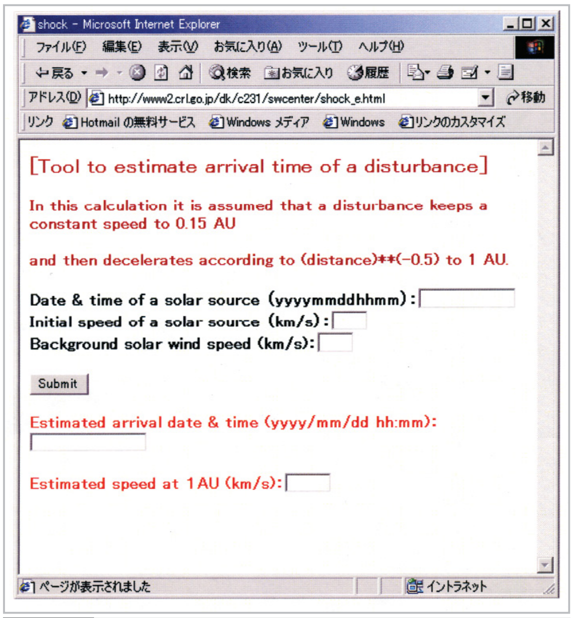

Fig.2 *GUI for predicting the disturbance arrival time*

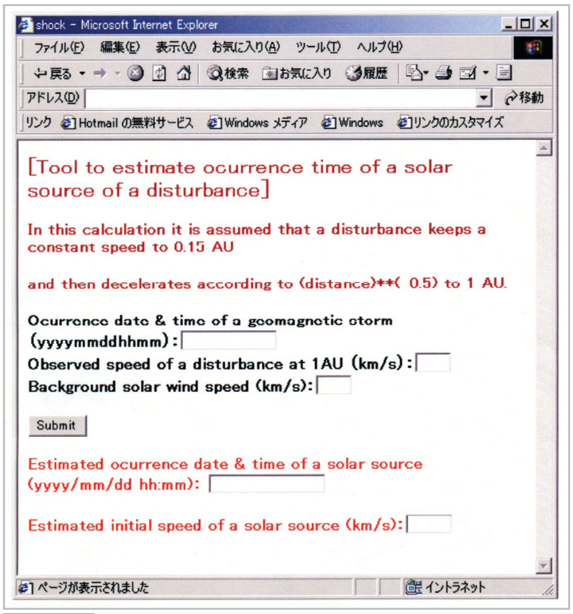

Fig.3 *GUI for predicting the time of occurrence on the Sun of a disturbance observed at the Earth*

3 Applications to Actual Events

3.1 Estimation of Disturbance Arrival Time

The model was validated using 28 events in which a significant shock was observed near the Earth. The disturbance arrival time, the time of occurrence of the associated event on the Sun, CME velocity, and the prediction error for arrival time are presented in Table 1. The CME velocity is taken from the catalog of CME velocities created through collaboration between the NRL and the Center for Solar Physics and Space Weather of the Catholic University of America, in which CME velocities are calculated with linear fitting methods for CME events observed by SOHO/LASCO. The prediction errors appear smaller for higher initial CME velocities. Fig.4 shows the distribution of the transit time of interplanetary

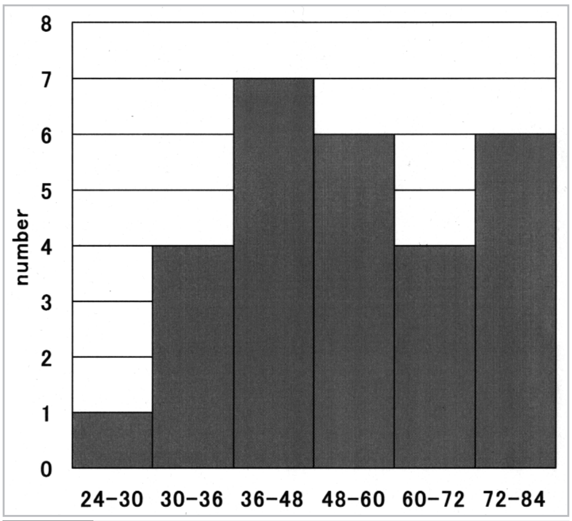

Fig.4 *Distribution of transit time of the interplanetary disturbance*

Table 1 *Interplanetary disturbance arrival time at the Earth and the associated event*

ocurrence time of disturbances at the Earth (UT)	type of geomagnetic disturbances	comments	ocurrence time of solar events (UT)	CME speed (km/s)	predicted arrival time of disturbances (UT)	ΔT (hour)
2000/04/06 16:31	SSC	halo CME, DSF, C9.7/2F (N16W66), type II, SEP	2000/04/04 15:11	1188	2000/04/06 16:31	0.0
2000/05/23 14:00		partial halo CME, C7.6/1N (S15W08), type II	2000/05/20 05:26	738	2000/05/22 21:22	−16.6
2000/06/08 09:10	SSC	halo CME, C9.7/2F (N16W66), DSF, type II, SEP	2000/06/06 14:58	1119	2000/06/08 14:29	5.3
2000/07/15 14:38		halo CME, X5.7/3B (N22W07), type II, SEP	2000/07/14 10:03	1674	2000/07/15 19:41	5.1
2000/07/28 06:35	SSC	halo CME, M8.0/2B (N06W08), type II	2000/07/25 02:43	528	2000/07/28 21:16	14.7
2000/08/11 18:45	SSC	halo CME	2000/08/09 16:30	702	2000/08/12 13:19	18.6
2000/09/06 17:01	SI	partial halo CME, DSF (N13W38)	2000/09/04 06:06	849	2000/09/06 21:01	4.0
2000/10/12 22:28	SI	halo CME, C6.7/1F (N01W14)	2000/10/09 22:32	579	2000/10/13 13:11	14.7
2000/10/28 09:52	SSC	halo CME, C4.0, SEP	2000/10/25 08:45	770	2000/10/28 04:47	−5.1
2000/11/10 06:26	SSC	halo CME, M7.4/3F (N10W77), SEP	2000/11/08 22:42	1345	2000/11/10 17:11	10.7
2000/11/29 01:00		halo CME, X1.9/2B (N20W23), type II	2000/11/25 18:33	671	2000/11/28 20:09	−4.8
2001/01/13 01:50	SSC	halo CME	2001/01/10 00:54	832	2001/01/12 17:39	−8.2
2001/01/31 08:04	SSC	partial halo CME, M1.5/1N (S04W59)	2001/01/28 15:40	916	2001/01/31 03:17	−4.8
2001/04/08 11:00	SSC	halo CME, X5.6/SF (S21E31)	2001/04/06 19:10	1270	2001/04/08 14:54	3.9
2001/04/11 13:43	SSC	halo CME, M7.9/2B (S21W04), EIT wave, dimming, type II	2001/04/09 15:20	1192	2001/04/11 12:52	−0.8
2001/04/13 07:34	SSC	halo CME, M2.3/1F (S22W27), type II	2001/04/11 12:56	1103	2001/04/13 11:29	3.9
2001/04/18 00:46	SSC	partial halo CME, X14.4/2B (S20W85), type II, SEP	2001/04/15 13:19	1199	2001/04/17 15:40	−9.1
2001/04/28 05:00	SSC	halo CME, M7.8/2B (N17W31)	2001/04/26 11:26	1006	2001/04/28 15:57	10.9
2001/08/17 11:02	SSC	halo CME, DSF, arcade	2001/08/14 16:01	618	2001/08/17 21:44	10.7
2001/09/25 20:25	SSC	halo CME, X2.6/2B (S16E23), SEP	2001/09/24 09:32	2402	2001/09/25 12:38	−7.8
2001/09/30 19:24	SSC	halo CME, M3.3/2N (N10E18), type II	2001/09/28 08:10	846	2001/09/30 20:29	1.1
2001/10/11 17:00	SI	halo CME, type II	2001/10/09 11:30	973	2001/10/11 18:50	1.8
2001/10/21 04:47	SSC	halo CME, X1.6/2B (N15W19), type II, SEP	2001/10/19 16:13	901	2001/10/22 05:35	24.8
2001/10/28 03:18	SI	halo CME, X1.3/2B (S17W20), EIT wave, dimming, type II	2001/10/25 14:42	1092	2001/10/27 19:29	−7.8
2001/11/06 01:51	SSC	halo CME, X1.0/3B (N06W18), type II, SEP	2001/11/04 16:03	1810	2001/11/06 03:28	1.6
2001/11/24 05:54	SI	halo CME, M9.9/2N (S15W34), dimming, SEP	2001/11/22 22:32	1443	2001/11/24 13:20	7.4
2001/12/29 04:56	SI	partial halo CME, M7.1/1B (N08W54), type II	2001/12/26 04:32	1446	2001/12/27 22:11	−30.8
2001/12/30 19:38	SI	X3.4, type II, SEP	2001/12/28 20:02	2069	2001/12/30 02:01	−17.6
					(average value of error)	0.9
					(dispersion)	11.8

disturbances calculated using values in Table 1. The transit time is 53.8 ±16.2 hours. Although the variance is large, it can be seen that a disturbance will reach the Earth in about 2 days.

Fig.5 shows the distribution of the prediction error of the arrival times. The mean prediction error is 0.9 ±11.9 hours. It can be seen from the distribution that the model used in the present study tends to predict a later-than-actual time of arrival of the disturbance. Fig.6 is a scatter diagram of the velocity of the disturbance observed near the Earth and of the velocity predicted from the model. A positive correlation can be seen between the two.

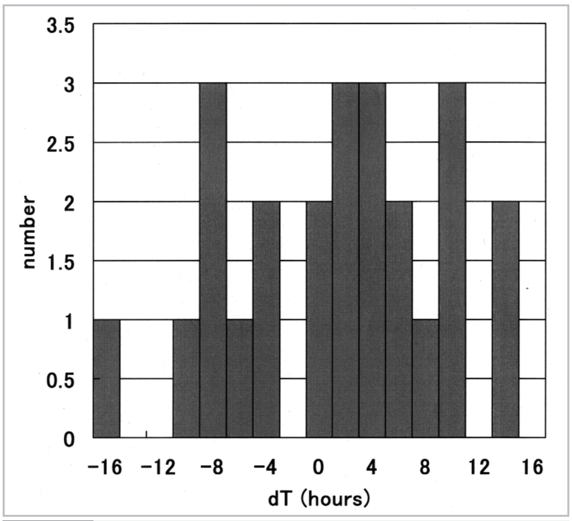

Fig.5 *Distribution of prediction error for interplanetary disturbance arrival time*

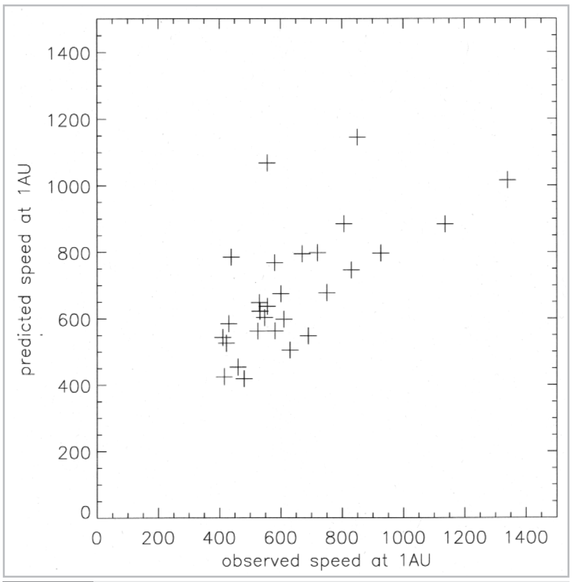

Fig.6 *Velocity of interplanetary disturbances observed near the Earth vs. the model-predicted values*

3.2 Estimation of the Time of Occurrence of a Solar Event Associated with an Interplanetary Disturbance

Fig.7 shows the distribution of the difference (prediction error) between (i) the time of occurrence of the associated solar event, predicted using Eqs. (3), (4), and (5) based on the disturbance arrival time at the Earth, its velocity, and the background solar wind velocity; and (ii) the observed time of occurrence of the associated solar event shown in Table 1. The mean prediction error is −7.1 ±11.1 hours, and it can be seen that our model tends to predict an earlier-than-actual occurrence of the associated event.

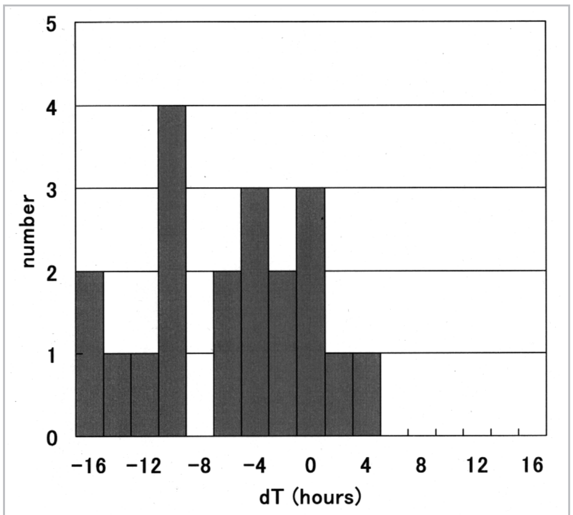

Fig.7 *Distribution of prediction error for time of occurrence of disturbance-causing events*

Fig.8 shows the correlation between longitude and the ratio of two CME velocity values: that observed by the SOHO/LASCO and that predicted from the model based on solar wind observations near the Earth (at 1 AU). The observed velocity tends to be smaller than the predicted velocity for events that occur near the central regions of the Sun, while the opposite holds true for events that occur in the limb regions. This is believed to be due to the fact that the velocity component perpendicular to the direction of the CME is mainly observed for events that occur in the central regions, while the velocity component parallel to the main direction of the CME is observed

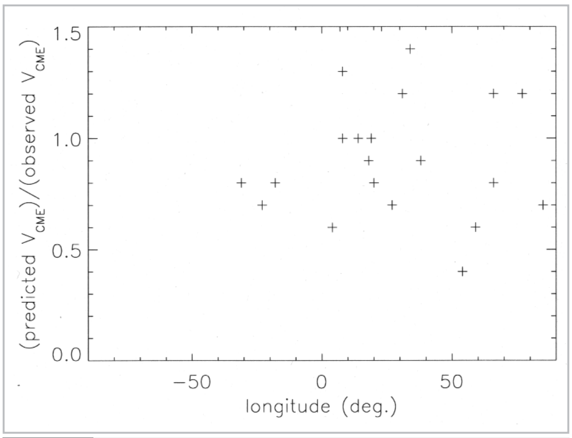

Fig.8 *Longitudinal distribution of the ratio between observed CME velocities and those predicted by the model*

for events occurring in the limb.

3.3 Examination of Parameters Used in the Calculations

The distance R_1 at which the disturbance begins to decelerate and the factor α that determines the deceleration may take values that are different from those assumed above. In this study, the two values were fixed since they are difficult to obtain directly from observation. It is possible, however, to determine R_1^{α} from the relationship in Eq. (4) using the CME velocity actually observed, the velocity of the disturbance observed near the Earth, and the background solar wind velocity. Therefore, by assuming that either R_1 or α is

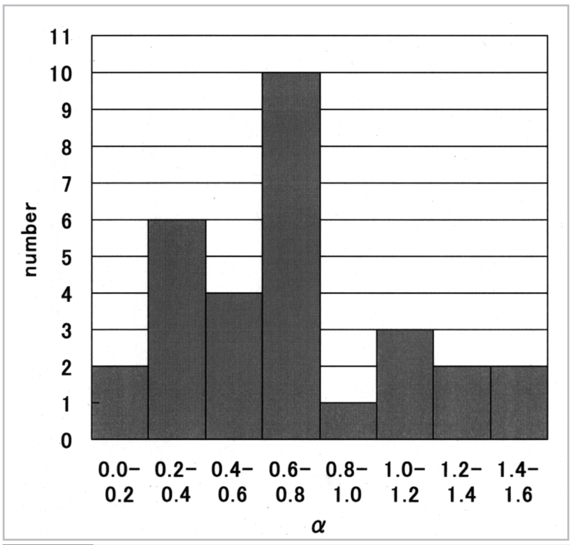

Fig.9 *Distribution of R_1 assuming α = 0.5*

known and has a constant value, it is possible to obtain a distribution of the other, unknown parameter. Fig.9 shows the distribution of R_1 when $\alpha = 0.5$. In this case, the mean value of R_1 is 0.19 ±0.23 AU. On the other hand, Fig. 10 is the distribution of α when $R_1 = 0.3$. The mean value of α is 0.7 ±0.4. Although both distributions display large variance, R_1 was smaller than the assumed value of 0.3 AU, and α was larger than the assumed value of 0.5. These results imply that deceleration may begin nearer to the Sun than assumed. In practice, St. Cyr et al.[18] have reported a case of deceleration observed within the field of view of the SOHO/LASCO.

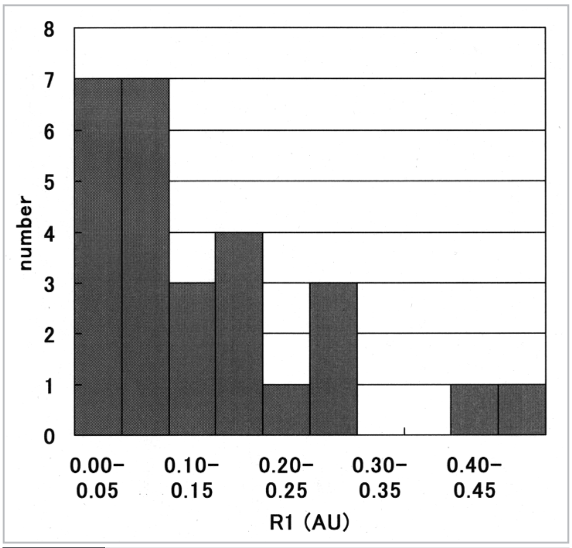

Fig.10 Distribution of α assuming $R_1 = 0.3$

In this study, it was assumed that the background solar wind velocity is constant. Some observation results to date have indicated that solar wind acceleration ceases within a distance of 10 solar radii[19], and so the prediction error resulting from this assumption is considered to be minor for high-velocity disturbances. However, when a disturbance arrives at the Earth after passing through a region of slow solar wind (such as a sector boundary), the effect of the interaction between background solar winds and the disturbance may result in larger errors. The observed CME velocities appear to display longitudinal dependency due to projection, as shown in **3.2**. It may be necessary to correct the data for the location of the occurrence of the disturbance and for its spatial distribution.

4 Conclusions

Although the model used in this study was a relatively simple one, its predictions exhibited relatively high precision. A precise prediction of the arrival time of a disturbance from the Sun to the Earth means that a precise estimation can be made of the time of occurrence of a disturbance-causing solar event based on near-Earth observations of interplanetary disturbances. Such attempts are important for a greater understanding of the physics of the Sun-Earth connection system. In the future, it should be possible, using methods such as MHD simulations, to make highly precise predictions that take into consideration the 3-D structure of the disturbance and the interactions between the disturbance and background solar wind structure. Furthermore, the STEREO (Solar Terrestrial Relation Observatory) planned for launch by NASA in 2005 is expected to enable further observation of the velocity and propagation of disturbances toward the Earth[20].

The CME catalog of SOHO/LASCO observation used in the present study is created and maintained through collaboration between NRL and the Center for Solar Physics and Space Weather of the Catholic University of America. The SOHO satellite was launched as a joint project of the ESA and NASA.

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