Solar Radio Emission as a Criterion for Solar Proton Event Warning

J. D. FLETCHER*
North American Aviation, Inc., Downey, Calif.

The use of solar radio emission as an indication of impending proton arrival from a solar flare is discussed. Specific characteristics of solar radio emission on fixed frequencies have been found to be associated with solar flares that are proton emitters. These signal characteristics are distinguishable from nonproton emitting flares. Fixed frequencies between 1000 and 3750 Mc tend to show recognizable signal characteristics that will give a warning time from a minimum of 30 min to an average of 2 hr before the arrival of protons near the earth. The correlation between solar radio emission and solar flares and between solar flares and solar cosmic ray or proton events has been known for quite some time and has been well established. If the knowledge were available that a particular solar flare was capable of producing protons, and that, within a relatively short period of time, the protons would be observed in the vicinity of the earth, the warning time gained would be used effectively in many ways.

BOISCHOT[1] described a particular type of radio emission whose characteristics showed a burst that lasted for tens of minutes and whose source did not remain fixed in the solar atmosphere. The source appeared to move outward with speeds up to 1000 km/sec. It followed that any continuum radiation (i.e., radiation showing smooth, even characteristics over a broad band of frequencies) would be called type IV, which orginally pertained to a specific characteristic in the meter wavelengths. The definition was later extended to include any long-period continuum emission in any part of the radio spectrum that follows a flare (Boischot and Pick[7]). These definitions of type IV, however precise, were not adequate for solar proton event warning.

Many solar investigators—Boischot,[1] Thompson and Maxwell,[2] Pick-Gutmann,[3] Kundu,[4] Wild,[5] and Bell[6]—have found that a significant relation exists between the occurrence of a spectral type IV solar radio outburst in association with a flare and an impending bombardment of protons in the vicinity of the earth. The very high correlation between solar proton events and type IV radio emission appeared to be very encouraging as a means of developing a solar proton event warning system.

It appears from the preceding definitions that a type IV event can be recognized by the use of spectral solar radio receiving equipment. The use of solar radio spectrum analyzers, however, would entail the use of equipment whose complexity would not allow simple analytical procedures. It was necessary to investigate the development of a simplified technique of reception and analysis of the solar radio emission. It was also realized that, if the radio signal associated with a proton emitting flare could be recognized at a single frequency, a system might be developed which would be compact enough for use onboard spacecraft or for widespread terrestrial observations.

The literature was nearly void of cases where investigators had sought for the relationship between the characteristics associated with a fixed frequency solar radio signal and the existence of associated protons. One exception was Kundu and Haddock.[8] While comparing centimeter-wave solar bursts with centimeter-wave solar outbursts, they stated that a microwave outburst in the centimeter wavelengths, described as a simple burst with a postburst increase (Covington[9]) with a typical duration of from 10 to 20 min and a rise time of 1 to 3 min, may have solar cosmic rays as associated phenomena. A simple burst, as defined by Covington, is a burst with an intensity greater than 7.5×10^{-22} w-m^{-2} (cm/sec)$^{-1}$ and of relatively short duration. A postburst increase is described as a case in which the flux level remaining after a simple burst is higher than the flux level prior to the occurrence of the simple burst. The realization that a fixed frequency might display characteristics recognizable as being associated with a proton event prompted further investigation.

The initial investigation entailed the use of basic data published in the International Astronomical Union Quarterly Bulletin (IAU) and supplemented by data published by the Central Radio Propagation Laboratory (CRPL) for the period 1956–1961. The purpose of the initial study was to determine the feasibility of the use of a single frequency in the establishment of a solar proton warning system. The time of occurrence of solar radio emission data used in the analysis was compared with proton events selected from a list compiled by Malitson and Webber.[10] If the time of the associated radio emission was not available from this list, a careful study was made of all available observations (IAU, CRPL, or from original records) for a period up to 24 hr prior to the proton arrival time as given by the same list prepared by Malitson and Webber. The 23 solar cosmic ray events used in the analysis were those whose total integrated fluxes were $\geqslant 1 \times 10^7$ protons-cm^{-2} greater than 30 Mev as reported by Malitson and Webber. There is no absolute assurance that every solar radio event investigated was the actual one that was associated with the proton emission, but the possibility of nonassociation is minimal.

Reproductions of original records of fixed frequency solar rf bursts associated with outstanding proton events were studied for signal characteristics indicative of these proton events prior to the actual formal analysis. After studying these records, it was noticed that each of the associated signals had several general characteristics that preceded the arrival of the protons at the surface of the earth, these characteristics being specifically different for each received frequency.

It may be observed from Fig. 1 that the characteristics of the solar radio signal have obvious differences from one frequency to the next. The top trace represents the arrival time of the solar cosmic rays. The other plots represent the

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* Research Specialist, Space and Information Systems Division.

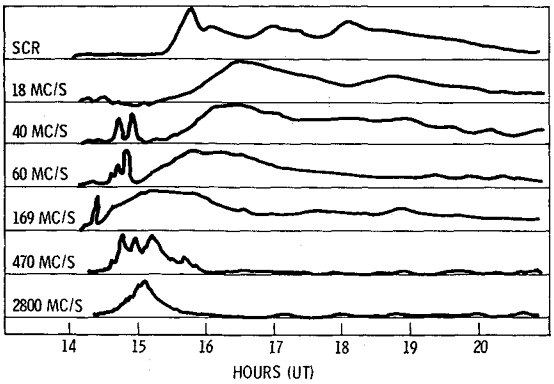


Fig. 1 Typical proton event and solar radio relationship (from Boischot and Warwick[11]).

radio flux changes with respect to time. The characteristics of the rf signal at the higher frequencies differ somewhat from those at lower frequencies, and the associated causes are not generally agreed upon (Boischot and Warwick [11]). But the fact remains that rf signal is available for analysis at these higher frequencies prior to the arrival of the solar protons. In particular, it became evident that the characteristics of signal duration and maximum flux density of the associated rf bursts were related to the subsequent proton events, with the actual numerical values for these characteristics being different for each frequency.

It was decided that signal duration and maximum flux density would be worthwhile signal characteristics to study in more detail for proton event warning.

A statistical analysis was made on data taken primarily from the IAU Quarterly Bulletin for the determination of optimum frequencies and resultant signal characteristics that might be used for proton event warning. The initial characteristics used were signal duration (in minutes) and signal maximum flux density $[10^{-22}\ \mathrm{w \cdot m^{-2}\ (cm\ /sec)^{-1}}]$. The object of the statistical analysis was to determine the optimum frequencies and associated signal characteristics that would give the highest probability of warning success (PWS) and the lowest false alarm ratio (FAR).

Probability of warning success (PWS) is defined as

$$\mathrm{PWS} = \frac{\text{rf successes}}{\text{rf successes} + \text{rf failures}}$$

where an rf success is defined as a case in which the signal, received at a solar radio observatory at a particular frequency, is associated with a prescribed proton event and meets the signal characteristics specified. An rf failure is defined as a case in which a signal associated with a prescribed proton event did not meet the specified signal characteristics. Thus, PWS is the probability that, if a proton event of a particular size did occur, a warning would be given with respect to certain signal characteristics.

False alarm ratio (FAR) is defined as

$$\mathrm{FAR} = \frac{\text{total signals with specific characteristic requirements}}{\text{total signals with characteristic requirements for which proton events followed}}$$

or

$$\mathrm{FAR} = \frac{\text{false alarm signals} + \text{proton event rf signals}}{\text{proton event rf signals}}$$

where a false alarm is a case where a characteristic signal is received and no ensuing proton event follows. Thus, FAR is the inverse of the probability that, if a specific solar rf signal characteristic is received, it will be followed by proton events of a particular size.

Two basic approaches were made to this initial analysis: a restrictive approach and a nonrestrictive approach. In the restrictive approach, the results are restricted in that the rf failure cases for the calculation of the PWS include stations that were in a geographical position to have observed associated rf, for a specific proton event, but did not report any signal observation, or else data were not available. If the observing station did not report any data, it was assumed that the station was in operation at the time of the rf event but did not receive any signal that met the signal characteristics requirements. The assumption that the observatory did receive a signal but that it did not meet the signal characteristics requirements may not be a valid one. Examination of original records from solar observatories have shown radio events for certain proton flares in which the signal characteristics were actually met but the rf data were not published in the IAU Quarterly Bulletin. The assumption that the station was actually in operation because it was in a geographical position to have observed the solar rf may be invalid also. The station may have been inoperative for many reasons, such as equipment failure, power failure, etc.

A nonrestrictive approach is defined as one in which the solar radio data for proton events included in the analysis were those that had associated radio data available for study with no assumptions or restrictions. Optimum frequencies were then determined by choosing the frequency or frequencies that would give the highest PWS and the lowest FAR for associated signal characteristics. The initial signal characteristics chosen were signal duration of 10 min or greater, and a maximum flux density of at least 150 flux units. It may

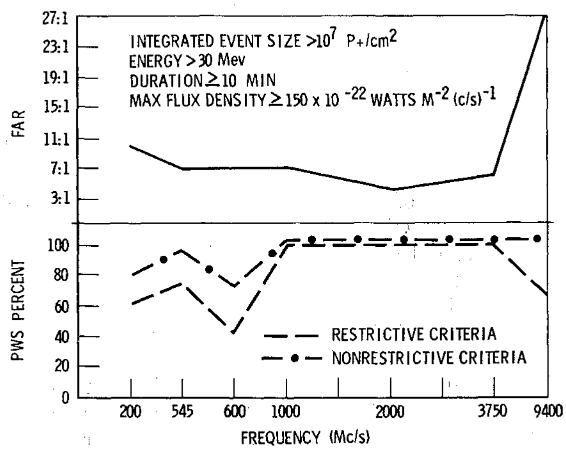


Fig. 2 Optimum frequency and false alarm calculations using IAU data.

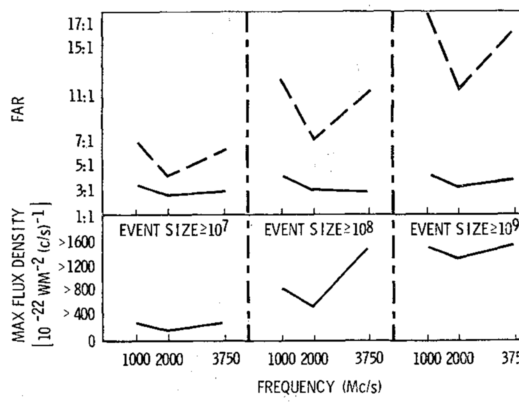
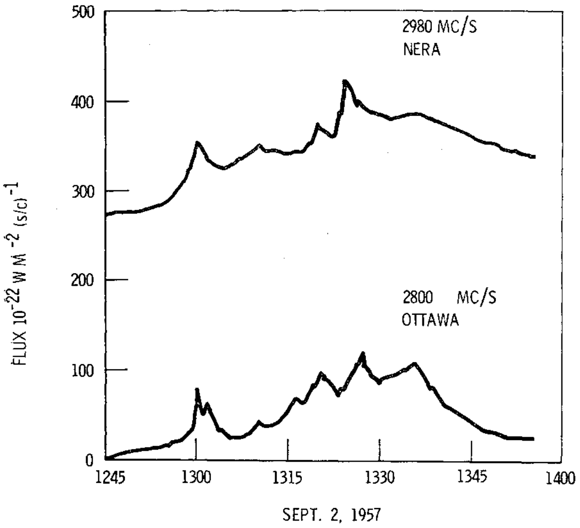


Fig. 3 The top shows false alarm ratios by event size and frequency for varied signal characteristics. The bottom indicates signal characteristic variations while maintaining 100% PWS.



IAU QUARTERLY BULLETIN DATA

	ST. TIME	MAX TIME	MFD	DURATION
2980	1257	–	429	45
2800	1247	1350	120	250

Fig. 4 Example of data normalization problems for simultaneous observations.

be seen in Fig. 2 that the optimum frequencies appear to lie in the range of 1000 to 3750 Mc/sec. It is also apparent that the lowest false alarm ratios are for frequencies near 2000 Mc/sec.

These results tend to agree with those presented by Das Gupta and Basu.[12] They show that large flares whose radio emission occurs near the time of the flare within the frequency range between 1000 to 3750 Mc/sec show the highest correlation of association with major flares.

Individual frequencies in the optimum range of 1000 to 3750 Mc/sec were studied further to see if the FAR could be lowered while still maintaining a 100% PWS. It was found that if an increased signal duration were considered and the maximum flux density varied so that a 100% PWS was maintained for each proton event size, the FAR could be further reduced. Figure 3 depicts the lowering of the false alarm ratio by frequency for event sizes of $\geqslant 10^7$, $\geqslant 10^8$, and $\geqslant 10^9$ protons-cm^{-2}. Also shown in Fig. 3 is the change in maximum flux density as the proton event size increases while still maintaining a 100% probability of warning success. It is also obvious from Fig. 3 that there is a direct relationship between the maximum flux density and proton event size. The fact that the maximum flux density tends to increase with event size might lead one to believe that the prediction of the size of the impending proton event might be achieved.

Even though relatively low FAR had been shown, especially for larger and more important events when the radiation problem is considered, the fact that the analysis had been based on such a small data sample made us consider the possibility of expanding the analysis. The results shown in Fig. 3 were based on the data from Nagoya, Japan, observing on frequencies of 1000, 2000, 3750, and 9400 Mc/sec. Since a single station is capable of taking solar observation for a maximum 12-hr period each day, flares occuring during the other 12-hr period were not included in the analysis. It appeared that, if a frequency within this range from the other hemisphere could be incorporated into the analysis, 2800 Mc/sec (Ottawa, Canada) or 2980 Mc/sec (Nera, Netherlands), for example, our data sample could be essentially doubled. It was found that this could not be done satisfactorily. Figure 4 shows some examples of the data normalization problems when many original records are considered. Figure 4 shows that the data reporting procedures may vary from station to station. Ottawa subtracts the mean daily flux prior to reporting observed data for publication, whereas Nera, on the other hand, did not. Both traces shown in Fig. 4 are for the same event at the same time and are both taken from original records obtained from each respective observatory. The table on the same plot shows the data as reported in the IAU Quarterly Bulletin. It is obvious that the results obtained by comparing the maximum flux densities from two or more different stations could not be used with a high degree of reliability but that the consistency of the signal characteristics shown in a single station did provide consistent data. Covington,[13] Ottawa (2800 Mc/sec), and Tanaka,[14] Nagoya (1000, 2000, 3750, 9400 Mc/sec), have stated that absolute fluxes reported are within $\pm$ 10% of the actual value. Since more data were readily available at 2800 Mc/sec and since this frequency was within the range that proved to be the most rep-

Table 1 Proton events recognized by Malitson and Webber or D. K. Bailey with total flux $\geq 10^6$ protons-cm^{-2} with energies > 30 Mev

No.	Date of event	Flux > 30 Mev	Source
1	Feb. 23, 1956	1.6×10^9	M & W
2	Aug. 31, 1956	3.0×10^7	M & W
3	Nov. 13, 1956	1.0×10^8	Bailey
4	Jan. 20, 1957	3.0×10^8	M & W
5	April 3, 1957	5.0×10^7	Bailey
6	June 21, 1957	1.5×10^8	Bailey
7	July 3, 1957	1.0×10^7	M & W
8	July 24, 1957	7.5×10^6	Bailey
9	Aug. 29, 1957	1.5×10^8	Bailey
10	Aug. 31, 1957	8.0×10^7	Bailey
11	Sept. 2, 1957	5.0×10^7	Bailey
12	Sept. 12, 1957	6.0×10^6	Bailey
13	Sept. 21, 1957	1.15×10^8	Bailey
14	Oct. 20, 1957	1.0×10^7	M & W
15	Feb. 9, 1958	5.0×10^6	M & W
16	March 23, 1958	4.0×10^8	M & W
17	March 25, 1958	6.0×10^8	Bailey
18	April 10, 1958	5.0×10^7	Bailey
19	July 7, 1958	5.0×10^8	M & W
20	July 29, 1958	8.5×10^6	Bailey
21	Aug. 16, 1958	2.0×10^7	M & W
22	Aug. 22, 1958	5.0×10^7	M & W
23	Aug. 26, 1958	5.3×10^7	M & W
24	Sept. 22, 1958	8.5×10^7	Bailey
25	May 10, 1959	1.2×10^9	M & W
26	July 10, 1959	8.0×10^8	M & W
27	July 14, 1959	2.0×10^9	M & W
28	July 16, 1959	3.0×10^9	M & W
29	Sept. 2, 1959	1.15×10^7	Bailey
30	Jan. 12, 1960	6.0×10^6	Bailey
31	March 29, 1960	6.0×10^6	Bailey
32	March 30, 1960	6.0×10^6	Bailey
33	April 1, 1960	2.7×10^6	M & W
34	April 5, 1960	2.0×10^6	M & W
35	April 28, 1960	2.5×10^7	M & W
36	April 29, 1960	1.75×10^8	Bailey
37	May 4, 1960	7.0×10^6	M & W
38	May 6, 1960	5.0×10^6	M & W
39	May 13, 1960	5.0×10^7	Bailey
40	Sept. 3, 1960	4.0×10^7	M & W
41	Nov. 12, 1960	2.7×10^9	M & W
42	Nov. 15, 1960	2.0×10^9	M & W
43	Nov. 20, 1960	6.0×10^7	M & W
44	July 11, 1961	2.0×10^6	M & W
45	July 12, 1961	1.0×10^7	M & W
46	July 15, 1961	1.25×10^7	Bailey
47	July 18, 1961	1.25×10^8	Bailey
48	July 20, 1961	9.0×10^6	M & W
49	July 28, 1961	4.4×10^6	Bailey
50	Sept. 8, 1961	3.0×10^6	Bailey
51	Sept. 10, 1961	3.75×10^7	Bailey
52	Nov. 10, 1961	8.0×10^6	Bailey

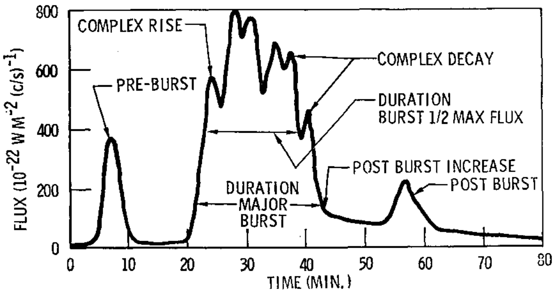


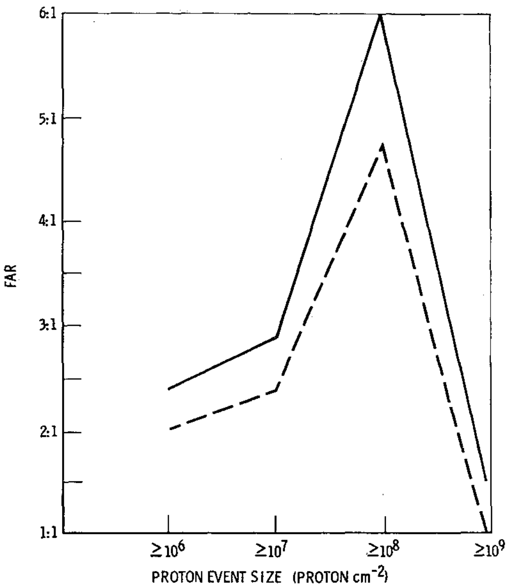
Fig. 5 Model fixed frequency centimeter-wave associated with solar proton event.

resentative in the initial analysis, it was selected for more detailed study.

Although the proton event list published by Malitson and Webber is thought to contain all of the proton events whose total fluxes are equal to or greater than 1×10^6 protons-cm^{-2} greater than 30 Mev, there were a number of events recognized by Bailey[15] to be of an equal magnitude in this range. A new proton list was therefore compiled which incorporated these events[16] as shown in Table 1. This list shows normalized values (from 20 to 30 Mev) for Bailey's events.

The original records of all of the outstanding solar radio events were obtained from Covington[13] at the National Research Council, Ottawa, Canada, observing on 2800 Mc/sec. Ottawa has been observing at this frequency since 1947. Only the records from 1956 to 1961 were used in the analysis because reliable observations of proton events have been made only during this period. The objective was the same as in the initial analysis. We wanted to find some characteristic of the solar radio emission associated with a proton emitting flare that was not recognizable when associated with a flare that was not an observable proton emitter.

The analysis of the original records obtained for 2800 Mc/sec has resulted in a model that is felt to be representative of the radio signal occurring at the time of a proton flare.



EVENT SIZE	MFD	DUR	POST INC	POST DUR
10^6	160	15	15	20
10^7	160	15	15	25
10^8	300	15	15	25
10^9	2500	40	>100	>100

EVENT SIZE	DURATION MAJOR BURST / DURATION 1/2 MFD
10^6	3.46
10^7	3.46
10^8	3.24
10^9	3.24

Fig. 6 False alarm ratios for combined Malitson and Webber and normalized Bailey proton event list using 2800 Mc/sec data and maintaining 100% PWS.

MALITSON & WEBBER & BAILEY EVENTS
OMITTING 11-13-56, 9-2-57, 7-15-61
PWS 84 PERCENT

SIZE	MFD	DUR	POST FLUX	POST DUR	DUR BUR / DUR 1/2 (MFD)	RR
10^6	340	15	15	20	3.75	24
10^7	340	15	15	25	3.75	24
10^8	360	15	15	25	3.75	31
10^9	2500	40	44	>100	3.24	51

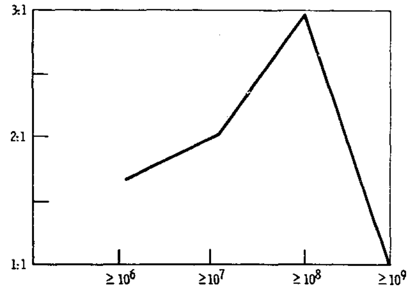


Fig. 7 False alarm ratios for 2800 Mc/sec data using Malitson and Webber and normalized Bailey events.

Figure 5 shows this representation. All of the characteristics shown in the model are not observable for every proton event. Most characteristics, however, are present.

The nomenclature of Fig. 5 is based primarily on the terminology developed by Dodson and Covington.[17] The features that were found to be important included those already found in the initial analysis, such as duration of major burst and maximum flux of the major burst. In addition, all proton events were found to have either a preburst, a complex rise, a complex decay, or any combination thereof. The most outstanding feature found, however, was the postburst increase. The postburst increase is sometimes accompanied by a postburst. It was noted that every proton

MALITSON & WEBBER EVENTS ONLY
PWS 100 PERCENT

SIZE	MFD	DUR	POST FLUX	POST DUR	DUR. BUR / DUR 1/2 (MFD)	RR
10^6	340	33	40	20	3.46	24
10^7	340	33	40	90	3.46	24
10^8	360	40	80	240	3.24	51
10^9	2500	50	>100	>100	3.24	51

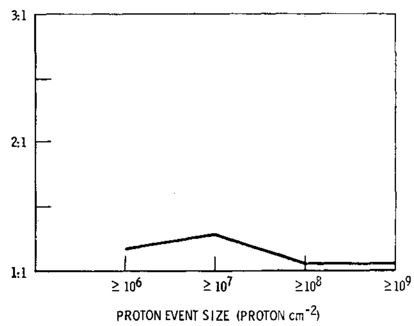


Fig. 8 False alarm ratios for 2800 Mc/sec using Malitson and Webber events alone with varied criteria in each case.

event, according to the combined list of both Malitson and Webber[10] and Bailey,[15] had the postburst increase as an observable feature. This observation agrees with the comment that was mentioned earlier, made by Kundu and Haddock,[8] that microwave bursts classified as simple by Covington, followed by a postburst increase, have solar cosmic rays as associated phenomena.

Additional salient features found while trying to establish proton event signal characteristics were 1) the rate of rise of the signal from the start of the major burst to the peak flux, in units of flux increase per minute; and 2) the ratio of the duration of the major burst to the duration of the major burst at one-half maximum flux density, with these times taken as shown in Fig. 5.

Figures 6 and 7 show how the reduction in the false alarm ratio as additional signal characteristics were added to the calculations. FAR's were calculated for the event sizes of $\geqslant 10^6$, $\geqslant 10^7$, $\geqslant 10^8$, and $\geqslant 10^9$ protons-cm^{-2} by using a maximum flux density, a duration of major burst, a postburst increase flux, and a postburst duration that was observable in every proton event whose accompanying flare occurred during the normal observational hours at Ottawa. The additional criteria of the ratio of the duration of the major burst to the duration of the major burst at one-half maximum flux density is shown to lower the FAR in every case for every event size.

After further examination of the solar radio data, it was felt that, if three of the proton events from the Bailey list could be considered as having total integrated fluxes that were smaller than stated, the analysis could be improved. These three Bailey events were then omitted from the list, and a recalculation of the FAR ratio was made. By omitting these events, the probability of warning success was lowered from 100 to 84%, but the FAR was lowered a very significant amount by adding the additional criteria, the rate of rise to signal maximum. These results are shown in Fig. 7.

Since the initial analysis used only the proton events as recognized by Malitson and Webber, we applied the same criteria to this list alone and calculated the FAR ratios as shown in Fig. 8. It was found that we are able to recognize every proton event equal to or greater than 10^6 protons-cm^{-2} total flux correctly, and that we would not have been falsely alerted in any case for events $\geqslant 10^8$ protons-cm^{-2}.

An investigation of this type has limitations because of the small sample size and the subjectivity of the analysis of the original records. Any final conclusions drawn from these results should be used with some caution. It is felt that the study has shown some significant characteristics that should be looked for when data is available during the forthcoming solar cycle. It is also felt that the data presented at this time show enough merit to justify the building of a system that would give warning of an impending solar proton event.

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