N88-14557

NEW APPROACHES TO SOME METHODOLOGICAL PROBLEMS OF METEOR SCIENCE

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ABSTRACT: Several low-cost approaches to continuous radioscatter monitoring of the incoming meteor flux are described. Preliminary experiments have been attempted using standard time-frequency stations WWVH and CHU (on frequencies near 15 MHZ) during nighttime hours. Around-the-clock monitoring using the international standard aeronautical beacon frequency of 75 MHz has also been attempted. The techniques are simple and can be managed routinely by amateur astronomers with relatively little technical expertise. If a source of reliable long-term funding could be found, it is proposed that a volunteer network of amateur radiometeor observers be established to provide a valuable long-term baseline system to supplement professional studies.

Time-series analysis can now be performed using relatively inexpensive microcomputers. Several algorithmic approaches to the analysis of meteor rates will be discussed. Implementation of these on personal computers allow fairly sophisticated algorithms to be performed at relatively low cost including production of the power-spectrum of the daily and hourly rates even if there are missing data points or segments. Methods of obtaining optimal filter predictions of future meteor flux are also discussed.

For nearly three-fourths of a century, C.P. Olivier, the founder of the American Meteor Society, collected data on the hourly rates of meteors seen by single visual observers. This information formed the basis of four catalogs (Olivier, 1960, 1965, 1974a, 1974b) giving the average visual meteor rates seen for each hour of the night during the year. Three of the catalogs were for the northern hemisphere and one for the southern hemisphere. The northern hemisphere catalogs were average rates over the years 1901 through 1958, 1959 through 1963, and 1964 through 1972. With the introduction of radioscatter detection methods, professional interest in such visual work (now done only routinely in the U.S. by amateur astronomers) waned considerably and in the decade following the publication of the last Olivier catalog, no serious attempt was made to update this compilation. Some recent developments now indicate that a radiometeor rate catalog based on amateur observations and linked statistically to visual and radar meteor rates is feasible and valuable.

First, it is becoming increasingly expensive for professional meteor observatories to maintain high-power radio transmissions on the continuous basis needed for a world-wide, routine patrol of meteor flux. Secondly, amateur radio operators and amateur astronomers around the world are presently acquiring receiving equipment with a sensitivity comparable to that in the hands of professional radio astronomers of one or two decades ago. Thirdly, these same amateurs are now in possession of one or more microcomputing systems which are capable of tabulating, storing, and processing large amounts of meteor monitoring data continuously and unattended.

In an attempt at harnessing this large pool of unused talent, the American Meteor Society has carried out some preliminary experiments involving the use of low-power radio beacons or other readily available ambient signals to estimate the meteor flux. The immediate goal of this work is to use presently active, visual meteor observers to calibrate each radio system back to the set of visual hourly rate observations that were obtained in the years before routine radioscatter observations were available.

The purpose of this paper is to review some of the amateur radio meteor work which has already been done by our group of observers and others and to sketch some of the methodology we hope to bring to bear on the problem of defining a radio equivalent of the visual rates. In the long-term, it is hoped that an index of visual/radio meteor activity (comparable in reliability to the familiar sunspot number/10 cm flux index of solar activity) can be developed.

Members of the American Meteor Society were among the first amateur astronomers to obtain scientifically useful VHF observations of radio meteors (HOUSTON, 1958). But domination of the field by professionals and interest in radioscatter for defense communications soon led to a hiatus in its use for serious amateur work at least in North America. In 1983, as a part of the amateur observational activities of the International Halley Watch, an attempt was made by the AMS to revive interest in amateur observations, particularly by those in North America. Japanese amateur observers already had an active radio meteor group and were making observations of the Halley-related showers well before the critical 1984-88 period. It was hoped North American amateur astromomers could follow their lead. Some of the results reported here were obtained as a part of IHW activities, but the program to maintain a continuous radio meteor patrol is the responsibility of the AMS.

Amateur meteor observers in Japan and Europe have carried out a number of interesting passive radioscatter experiments over the last decade. In Japan, the results of the Nippon Meteor Society and the FM Meteor Society have been especially noteworthy and sophisticated. Their work is based mainly on observations of domestic FM radio transmissions around 80 MHz and have been carried out daily for several years (FUKUDA, 1982; SHIMODA, 1982, 1983; SHIBATA, 1983a; SUZUKI, 1982, 1983). While these data are extremely valuable for flux determinations because they have been made daily for several years, they are not continuous over a full 24-hour period. Typical European amateur results with a similar degree of technical sophistication have been described by SCHIPPKE (1981). Results on frequencies of approximately 28, 50, 63, and 144 MHa are described in the most detail, but some observations in the HF bands were apparently also tried.

In North America, astronomically useful amateur radiometeor observations have lagged considerably behind those obtained in Europe and Japan. There are several reasons for this which should be mentioned. First, ambient radio transmissions in the 30-50 MHz range, until recently, have been mainly of an intermittent nature. In the 50-89 MHz television bands, the transmissions are reasonably continuous, but strong local stations are often found on every available channel. In the commercial FM band (89-108 MHz) station crowding has become so chronic that a "clear" channel is almost never found. While meteors can certainly be detected on North American television and commercial FM transmissions, the transmitter powers are so high, the broadcast schedules so skewed (often avoiding the important early morning hours), and the stations so widely scattered that they really seem unsuitable for use as a meteor flux standard. The only results achieved in North America so far with a sophistication comparable to that available in Japan and Europe were obtained by PILON (1984) in Canada (Figs. 1, 2). Although outstanding from a technical point of view, unforeseen circumstances have resulted in termination of this volunteer program. Amateur radio operator M. Owen in Canton, New York has recently obtained additional FM observations and it is hoped this can help offset the loss of the Pilon program (Figs. 3, 4, 5).

In a paper circulated to members of the American Meteor Society, I proposed using available, low-power aeronautical beacons to serve as continuous monitoring devices for obtaining meteor flux information (MEISEL, 1977). In particular, the use of the standard 75 MHz frequency of the instrument landing system (ILS), was advocated. The first results using this frequency were obtained by BLACK (1983) in Florida and were described in several astronomical publications. When this system was later moved to an urban area (Atlanta, Georgia), however, it failed to perform properly because of overwhelming groundwave intensity.

Since the 75 MHz band is adjacent to the 73 MHz radio astronomy band, it is possible to modify published equipment designs (SWENSON and FRANKE, 1979) to use on this aeronautical channel. The feasibility of this has been demonstrated by G. Pokarney working with AMS Hawaii Group led by M. Morrow. Most of the major showers have now been sampled from this near-equatorial station using this modified equipment.

In January 1983, the Federal Communications Commission of the United States approved automatic beacon control for selected amateur radio bands including 28 MHz and 50 MHz. One AMS member, J. Hollar, pioneered transmissions in the 50 MHz band and several others are now planned. The main disadvantage of this approach is that transmitter facilities must be constructed and maintained.

The use of HF international broadcast frequencies for detecting meteors have been described (SETTEDUCATI, 1960), but because these broadcasts are generally limited in length and have frequencies which are changed seasonally to maximize ionospheric reflection, they are not really suitable for serious meteor studies.

Because of the well-known frequency dependence of meteor trail reflectivities, the highest degree of sampling completeness of meteor flux will be obtained with the lowest frequencies. Thus some efforts to find suitable HF frequencies have been made. In 1975, during the last sunspot minimum, it was possible to utilize the Time Standard transmissions of station CHU, Ottawa, Canada for nighttime meteor scatter observations on 14.670 MHz during the major showers from Geneseo, New York. By late 1984,

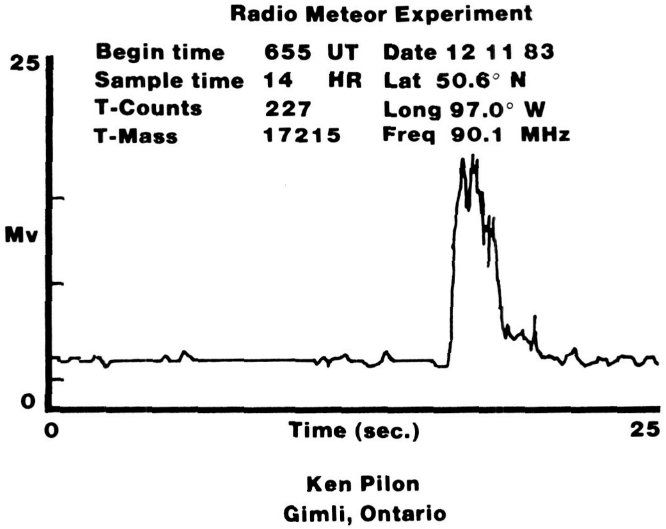

Fig. 1 Typical meteor echo measured as a forward scatter signal from a commercial FM radio station (from PILON, 1984).

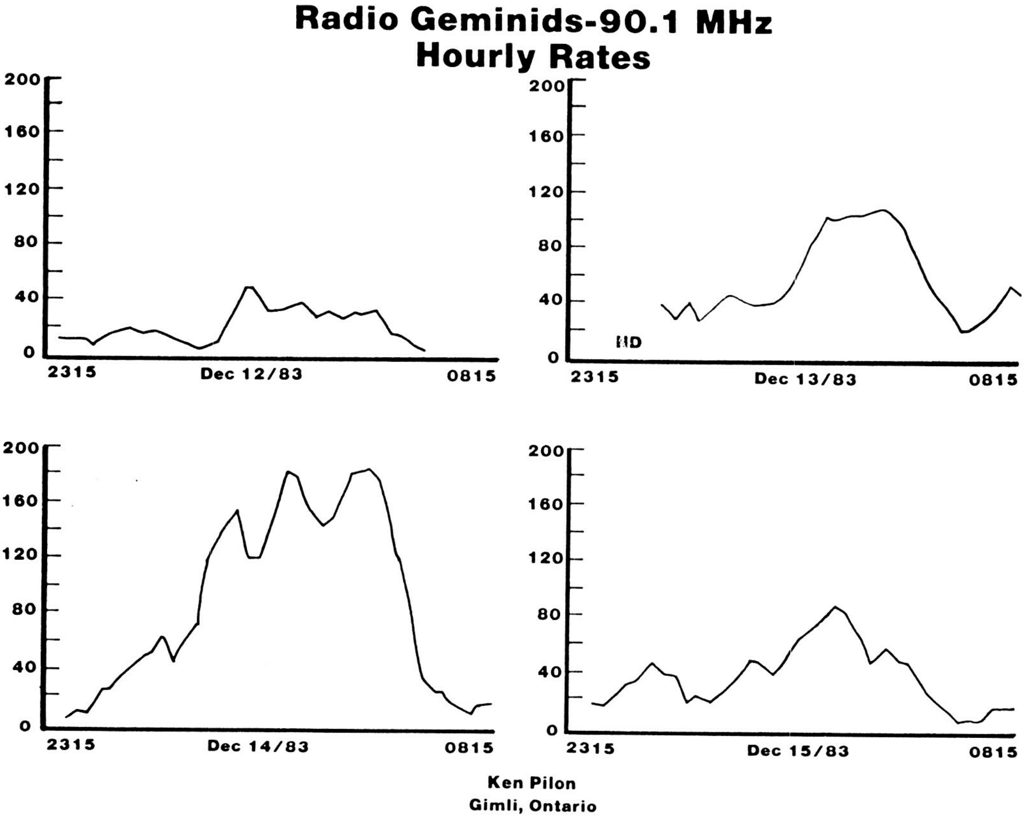

Fig. 2 Data rates measured as in Fig. 1 for the Geminids of December 12-15, 1983 (from PILON, 1984).

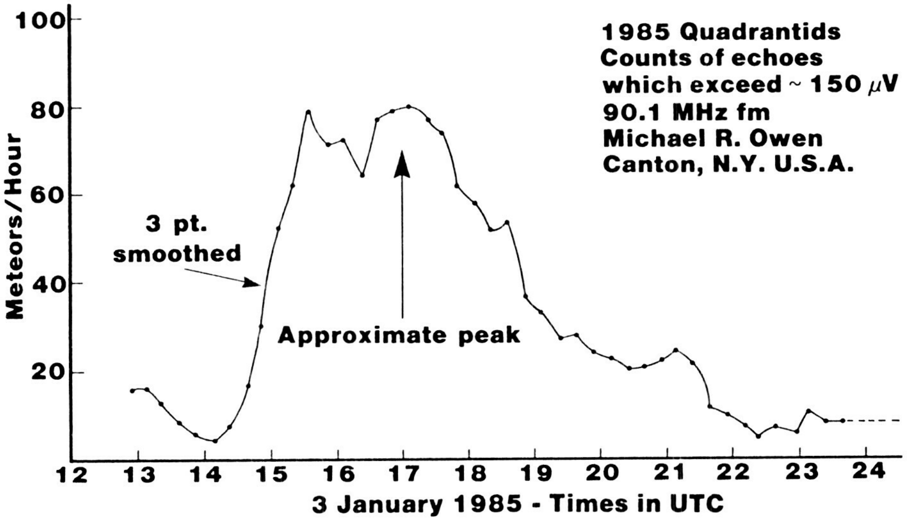

Fig. 3 Hourly counts during the Quadrantid shower, January 1985 M. Owen, private communication, 1985).

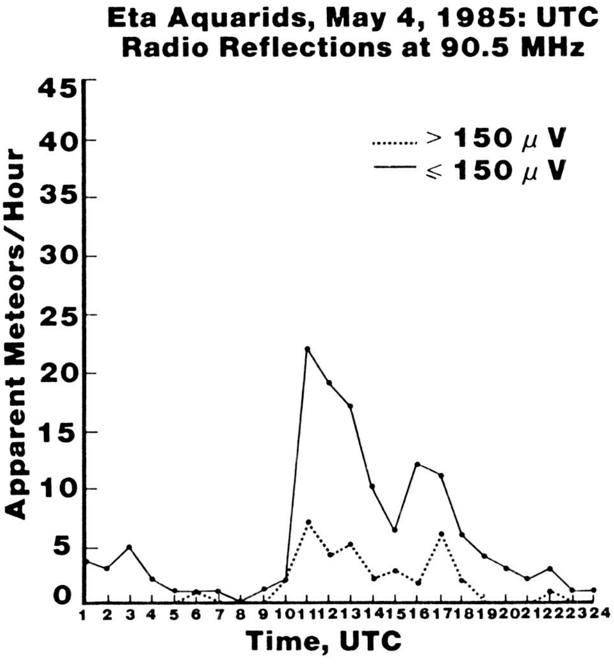

Fig. 4 As for Fig. 3, Eta Aquarids, May 4, 1985.

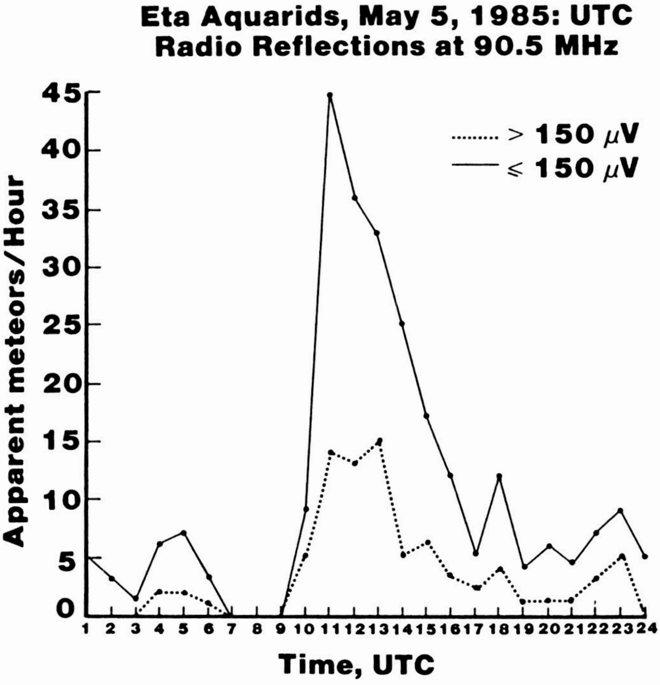

Fig. 5 As for Fig. 3, Eta Aquarids, May 5, 1985.

a low enough level of solar activity was achieved so that these were started once again (Figs. 6, 7). Similar results using WWVH on 15 MHz are being obtained by the AMS Hawaii Group (Fig. 8). All results so far indicate that at 15 MHz, the background flux is reasonably constant and the main effect of showers is to increase the number of longer-duration echos. This is in agreement with the findings of LINDBLAD (1980) who was studying the serial correlation of radio meteor echos.

A table of hourly meteor rates is really a time-series and so all of the powerful statistical techniques available from information theory for dealing with a time-series can be used to calibrate and analyze the data obtained. OLIVIER's first catalog of visual rates covers much too wide a range of years to be used without modification so as a part of the radio rate calibration, it is planned to go back to the original data and subdivide the information as much as possible (4 year blocks seem to be most reasonable since these represent two cycles of moonlight modulation of the results). The second and third catalogs were compiled for much shorter periods (5 years and 8 years) and therefore will not require quite so much work to repatriation. It is hoped that there will be enough extant material to at least go back to 1945 when radio rates began to be taken in a systematic way.

Time-series analysis of meteor data has rarely been undertaken, but it is a powerful technique that deserves to be used more. Among the few studies of meteors using time-series analysis are the papers by LINDBLAD (1980) and SHIBATA (1983b and 1983c). The LINDBLAD paper and the first SHIBATA paper deal with the problem of serial correlation of meteor rates. The second SHIBATA paper deals with prediction of meteor rates. I will return to the question of prediction presently. In all cases so far only equally-spaced data have been analyzed, but this is an unnecessary restriction.

It is well-known that time-series analysis can be approached most conveniently through the Fourier transform formalism (see SOLODOVNIKOV, 1960; RICE, 1954 or VAN DER ZIEL 1970 for example). The amount of literature dealing with standard time-series analysis is truly prodigous and no attempt will be made here to review much of it here. See the referenced works for a list of helpful texts and papers available in English.

There are several reasons why time-series analysis is not done more frequently. One is simply the large amount of computation required, but the wide availability of "micro" and personal computers will almost surely take care of this. Even if sufficient computational power is available, one of the most awkward problems to deal with is the question of what to do with samples taken at times and longitudes that are not equally spaced. A similar one is what to do with data with gaps due to interference or equipment problems. The data shown in the figures are good examples of such problems. In two papers, I have discussed several methods for handling some cases of particular astronomical interest (MEISEL, 1978, 1979). I will now emphasize and elaborate upon several approaches that are useful in analyzing meteor rate data.

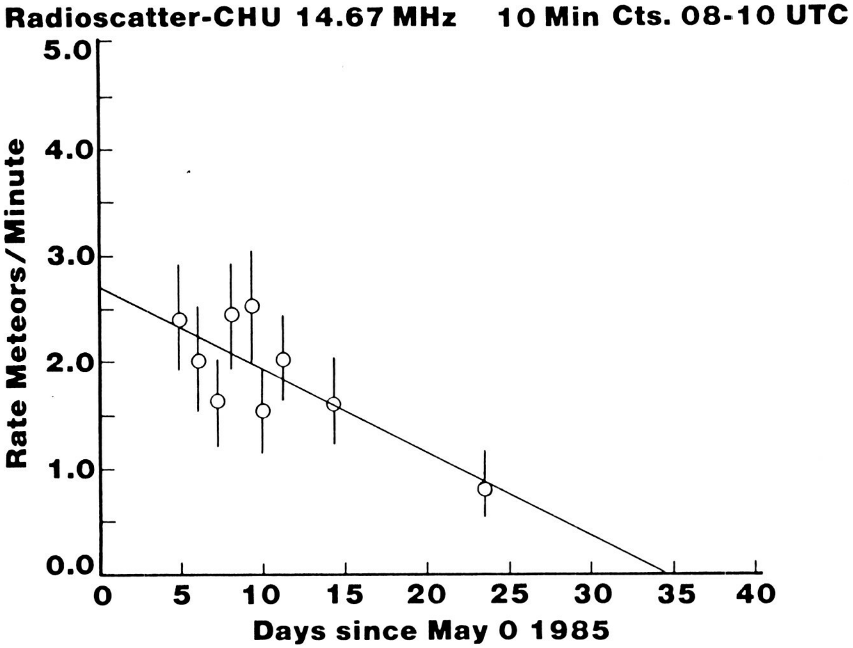

Fig. 6 Data rates measured in Geneseo, New York, using station CHU, Ottawa, Canada, on 14.670 MHz, May 1985.

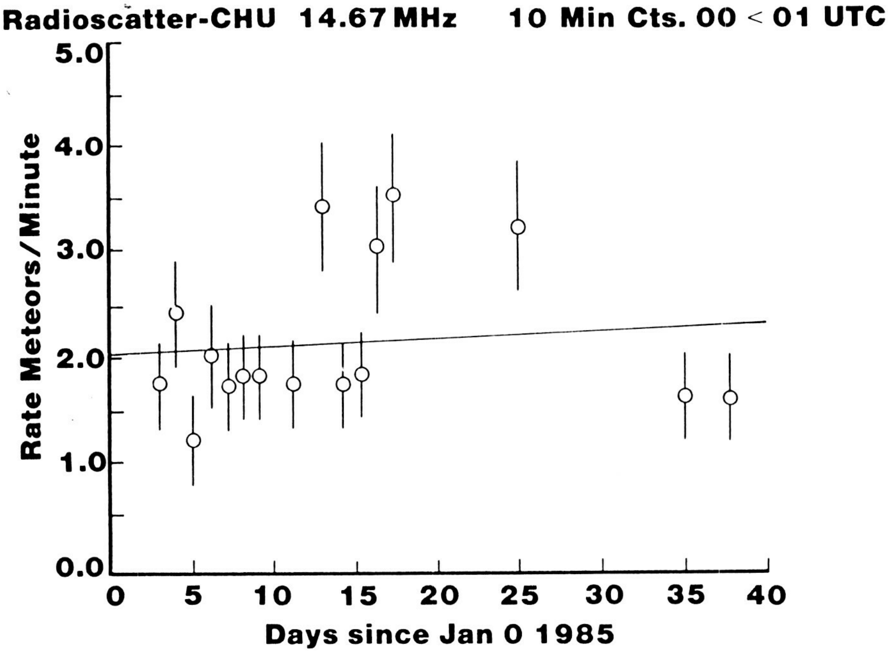

Fig. 7 As for Fig. 6, January 1985.

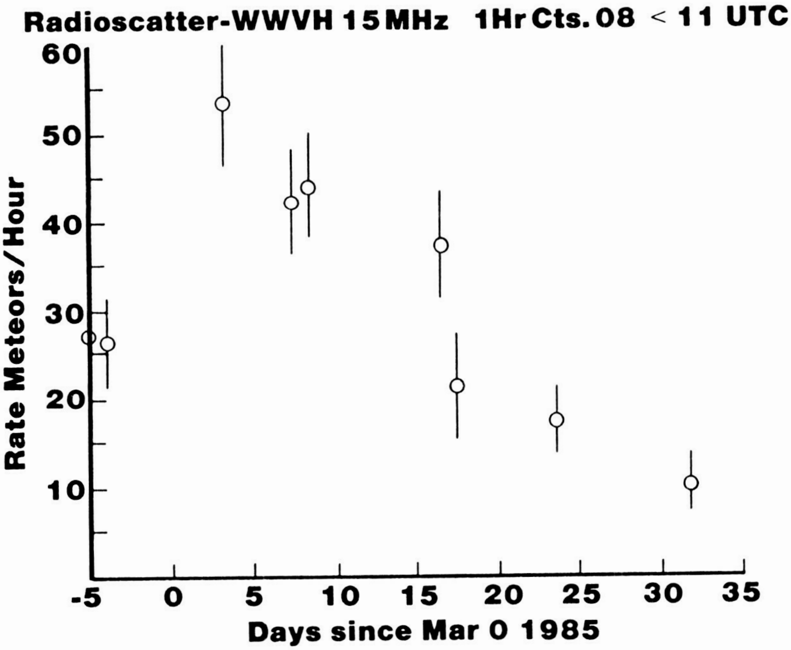

Fig. 8 As for Fig. 6, but using WWVH Honolulu, March 1985.

Interpolation of time-series data must be done with care since the usual polynomial methods can introduce distortions into the frequency domain. As discussed in my 1978 paper, the standard sinc (sin x/x) interpolation series for band-limited functions is only appropriate when the "jitter" from the equal spacing case does not exceed 20 percent. Beyond that one must use special orthogonal polynomials constructed by the well-known Gram-Schmidt or analogous process to obtain a proper interpolation. Some possible approaches to the interpolation problem are given in my previous papers and will not be detailed here. Once the data are in equal-interval form, the Fourier series or transform can then be computed by standard techniques.

To obtain the serial correlation, one simply squares and adds the corresponding Fourier coefficients. These will be estimates of the power-spectrum frequency points which by the Wiener-Khintchine theorem are the cosine transforms of each lag product of the finite autocovariance.

The interpolation to equal intervals followed by a discrete Fourier transform computation is a two-step process that should be followed only if one really desires to have the original data available for other purposes such as a catalog of meteor rates.

If it is desired to skip the interpolation step explicitly, a computationally more convenient approach to the problem is to calculate the standard least-squares estimates of the coefficients of a finite Fourier series. The resulting covariance matrix will, of course, not be diagonal because of the unequal sampling intervals even though the functions used are orthogonal over the continuous interval. If the inverse of the covariance matrix is triangularized by a technique that leaves the row-column order unchanged (Cholesky method, for example) then the coefficient vector that results from multiplication of the "observation vector" by the inverse of the covariance matrix will be the estimates of the Fourier coefficients corresponding to the equivalent equal interval problem. The resulting coefficients may then be used to directly estimate the power spectrum of the data. (This process is equivalent to a time-domain Gram-Schmidt interpolation followed by a discrete Fourier transform.)

Should it be necessary to know either the equally-spaced original data or the serial correlation, it can always be generated from the orthogonalized Fourier coefficients.

In the Fourier formalism of random processes, prediction is simply an extension of interpolation. The theory of "optimal filtering" as applied to a time-series can be found in communications engineering literature under various names: for example, Kalman-Bucy filtering, Wiener-Kolmogorov filtering, state-space filtering, digital filtering, or simply signal processing. Analogous techniques of time-series analysis are used widely in econometric forecasting. A particularly coherent and lucid treatment of the subject from an engineering standpoint can be found in the text by ANDERSON and MOORE (1979). Although this treatment is meant for a technical audience, the notation is consistent with econometric use and is therefore recommended.

SHIBATA (1983c) has applied the "Group Method of Data Handling (GMDH)" to attempt a prediction of meteor rates, but the adopted algorithm is simply one variation of an optimal filter method. SHIBATA derives the covariance properties of a composite meteor time-series from radio observations (SHIBATA, 1983b) and uses this to minimize the prediction sum-of-squares. While there is nothing pedigogically wrong with SHIBATA's Method, it does not seem to be general enough to be widely useful.

For the past several years, I have been carrying out experiments on optimal filter forecasts of solar and geophysical indices using a personal computer. Since the same methodology is applicable to meteor rate data, we will experiment with predicting future meteor rates based on the compiled catalog of past values.

The most general time-series that can be assumed is a combination of an autoregressive process (AR) and a moving average (MA) process called simply an ARMA process. However, before one can apply the powerful techniques available, one must be sure to be dealing with data having a zero mean. This generally means that all secular trends must be removed before doing the time-series analysis. The preferred method of doing this is through specially constructed orthogonal polynomials which do not distort the power-spectrum properties of the data (ANDERSON, 1971; FULLER, 1976). In the time-series analysis of meteor flux, an initial problem is obtaining the correct orthogonal polyomials for detrending the time series (LINDBLAD, 1980). While the familiar "11-year cycle" permits this is the case of solar-geomagnetic forecasting, such a "secular" trend is not available in meteor work. However, since the time-series behavior of the sporadic meteor flux is quite different from the various shower fluxes, it will be possible to treat each shower separately using the sporadic results as the "secular" trend. Such a separation will only be possible if the data are available world-wide, on a nearly continuous basis.

For initial numerical experiments, an assumption of statistical stationarity is appropriate and prediction by means of standard Wiener filter theory is applicable. The discrete time formulation of Wiener filtering is called Levinson filtering (ANDERSON and MOORE, 1979). The scalar version of the Levinson filter has been used to attempt prediction of solar activity and geomagnetic parameters. A Levinson (or Wiener) filter is constructed from the past covariance (power-spectrum) structure of the signal. This represents the AR part of the covariance. The remaining part of the total covariance is assigned to a MA process. Thus the first order (linear) prediction equation for the detrended residuals becomes,

$$F(n) = K^* \sum_{j} Rj^*F(n-j) + (1-K)^* \sum_{j} Sj^*F(n-j)$$

where K is an adjustable parameter which is equal to the ratio of the moving average variance to the total variance, the Rj are the ratios of the jth covariance component to the variance (= the zeroth order covariance component), and the Sj are the autoregression coefficients defined by the Levinson filter. The appropriate K can be found by trial and error from previous data, i.e., prediction of the last observed value using the remaining members of the series and choosing the K value that gives the best result. Details of the Levinson algorithm including a vector process version are given in ANDERSON and MOORE (1979) and will not be repeated here. The Levinson filter formulation requires equal intervals, but once the equal interval spectral components are estimated using the procedures outlined above, extension to a Levinson filter estimate is straight forward.

In many instances, it may be necessary to provide additional filtering (smoothing) to the prediction process. This is the domain of signal processing and is usually done again by trail and error. One particularly simple and useful technique is to use the LOGARITHM of the desired variable in the prediction equation. This is called exponential smoothing and its effect has well-known convergence properties (ANDERSON and MOORE, 1979). Other possible approaches abound in the signal processing literature and are beyond the scope of the present paper.

In conclusion it may be stated that amateur meteor observations made from several different locations around the world have now achieved a high enough level of technical sophistication to be useful for scientific purposes. These observers only need the support and guidance of the professional to be incorporated within the GLOBMET program. An outline for an initial effort involving standardization of amateur observations of meteor flux is the following:

1) Since ILS transmissions are available worldwide, we recommend that they serve as the nucleus of an amateur radio meteor network. On 75 MHz, the power available is quite low, but his is offset by the lack of interfering stations. At this frequency one obtains counts of mainly overdense trails so these should be easily statistically related to the standard visual hourly rates as compiled by OLIVIER and others. The frequency of 75 MHz is also high enough that ionospheric disturbance probabilities are very small. The 75 MHz transmissions are continuous and can be received during the daytime. Although VOR navigation beacons have the potential for enabling two-station triangulation of brighter meteors, the equipment required for doing this is apparently not readily available to amateur radio operators or amateur astronomers.

2) Although not numerous, there is a worldwide distribution of standard time/frequency stations that would permit nighttime monitoring of both underdense and overdense meteor echos at least during periods of low solar activity. The primary frequency for this would be 14-15 MHz. There are eight stations of this type which operate on 24 hour schedules. (Among these are: WWV, WWVH, CHU, JJY, RWM, RID, and RTA plus one due to start in Brazil. Station VNG operates continuously, but its top frequency is 12 MHz and it has not been established that useful meteor flux measurements could be made with it.) It is important to establish 75 MHz monitoring facilities within 30-300 km of these stations. Although these frequencies cannot be used continuously through the day or even through the years, the receiving equipment requirements are quite modest and readily available. It is possible that meteor scatter may be routinely observed using other sources of HF or VHF energy such as ionospheric sounders, but we have not explored this possibility.

3) The third standard frequency range for amateur monitoring could be in the 80-110 commercial FM band. While often not continuously available, this band does have the advantage of containing numerous high-power transmissions and readily available equipment. It will, however, not be an easy task to calibrate such radio observations with the rates obtained in other ways.

4) The choices for amateur meteor research using individually maintained beacon transmitters are 28 MHz and 50 MHz in North America and their equivalents elsewhere. These bracket the usual frequencies available for professional radioscatter transmissions and have less rigorous instrumental requirements than the higher VHF bands.

5) Automated data collection and reduction in real-time at the receiving station will be encouraged with particular emphasis on microcomputer usage. In particular, it will be possible not only to count the meteors automatically (SHIBATA, 1983a), but it will be possible to record the signal decay of individual echoes (PHILON, 1984). However, as our recent work shows, useful rate information can be obtained by simple manual recording of the number and aural character of echoes.

6) For the purpose of intercalibration, it would be useful if professional meteor observatories themselves would start monitoring meteor flux on as many of the frequencies mentioned above as possible. Data recording does not have to be sophisticated. Much of the Japanese amateur data has been obtained with two identical receivers for each frequency (one on frequency, one slightly off frequency) feeding a comparator network with the AGC voltages, and recording the output by chart recorder. Because of the relatively low-power of the 15 MHz and 75 MHz transmissions, the data rates on these frequencies are usually quite nominal.

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