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Calculating the Sensitivity of a Forward Scatter Setup for Underdense Shower Meteors

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Abstract

A method is outlined to calculate an "Observability Function" which is proportional to the number of shower meteors detected by a forward scatter setup under given (input) conditions, and assuming a constant actual meteor rate. This enables us to convert raw radio meteor rates to a better measure for a shower's activity.

1 Introduction

Before proceeding, I should remark that this paper is based on the 1958 paper (Hines, 1958) of Hines, although some important improvements were added by the author.

The central problem in amateur forward scatter meteor work today is that observers only present raw meteor rates or other data directly derived from the observation. This *is* a problem since there are a lot of time-dependent parameters dramatically influencing the sensitivity of the setup. However, these parameters can be evaluated, and this is exactly what we are up to.

As explained in (Wislez, 1996), reflection of radio waves off meteor trails is specular, which means effective reflection only takes place in a small area of the trail, near the reflection point. If we consider a specific transmitter T and a receiver R, this means scattered signals can only be received via those trails which lie tangent to one or another of the family of ellipsoids of revolution with T and R as common foci. Also note the trail has to lie above the horizons in T and R (Verbeeck, 1995). Since the geometry of ellipsoids is not all that simple, Hines first replaced the ellipsoids by cylinders (Hines, 1955), giving rise to the "cylindrical approximation" theory which gave satisfactory results for most showers if the distance between T and R was large enough (several hundred kilometers). However, for meteors travelling nearly parallel to the T–R path, the cylindrical approximation is not valid. So Hines decided to develop the real, "ellipsoidal" theory (Hines, 1958). We will directly describe this theory without looking at the cylindrical approximation.

The "potentially observable" shower trails — those that provide a specularly-scattered signal at the receiver — will first be located, and their distribution determined. The fraction of those that are actually observable — that provide a signal at the receiver exceeding some threshold — will then be found. Finally, the number of observable trails will be determined (up to a multiplicative constant) as a function of trail orientation by integrating over the spatial distribution.

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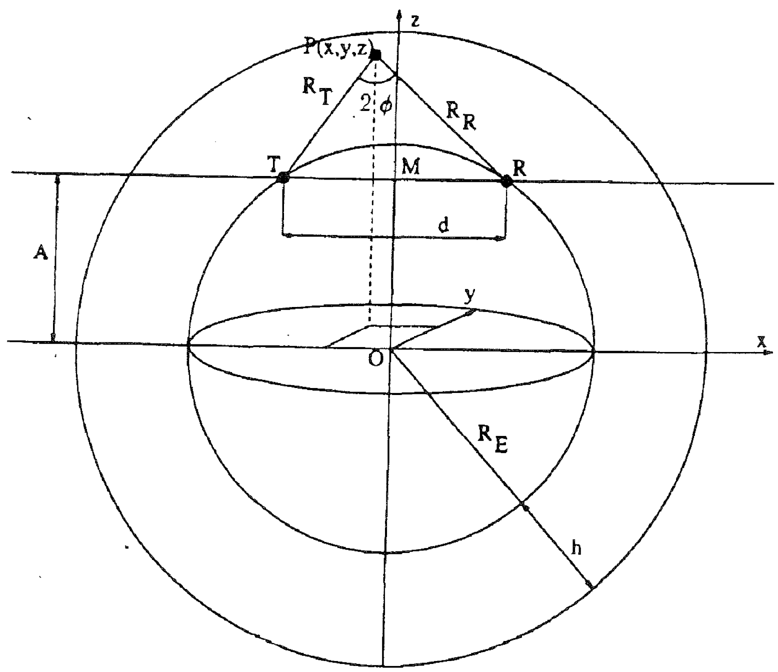

Figure 1: This figure shows the geometry of the discussed setup.

2 Conditions for specular scattering

Consider a forward scatter setup with transmitter T and receiver R, at a distance d (along a straight line through the Earth) from each other. Denote the Earth radius by R_E, and consider the right-handed orthonormal coordinate frame with origin in the center O of the Earth, x-axis in the direction T–R, and z-axis in the direction O–M, where M is the middle of T and R (see Figure 1). We only consider trails having a particular orientation (i.e., the direction of the shower radiant at a *fixed* time), specified by the direction cosines ξ, η, and ζ. We also suppose the trail passes through a point Q with coordinates (x_0, y_0, z_0) at a fixed standard height h above the (spherical) Earth's surface. A general point P on the trail will have coordinates $(x_0 + \xi s, y_0 + \eta s, z_0 + \zeta s)$, where s is the (signed) distance from Q to P. The coordinates of T and R are, respectively, $(-d/2, 0, A)$ and $(d/2, 0, A)$, with (see Figure 1):

$$A = \sqrt{R_E^2 - d^2/4}. \tag{1}$$

If we define R_T to be the length of TQ, R_R the length of RQ, R'_T the length of TP, R'_R the length of RP, and τ and ρ the angles between the axis of the trail and the directions TQ and RQ, respectively (see Figure 2), then the cosine rule for the triangles TPQ and RPQ implies:

$$R'_T = \sqrt{R_T^2 + s^2 - 2sR_T \cos\tau} \tag{2}$$

and:

$$R'_R = \sqrt{R_R^2 + s^2 - 2sR_R \cos\rho}. \tag{3}$$

Taking the second order Taylor expansion of these expressions in s around $s = 0$ yields:

$$R'_T \simeq R_T + \cos\tau \cdot s + (\sin^2\tau / 2R_T) \cdot s^2 \tag{4}$$

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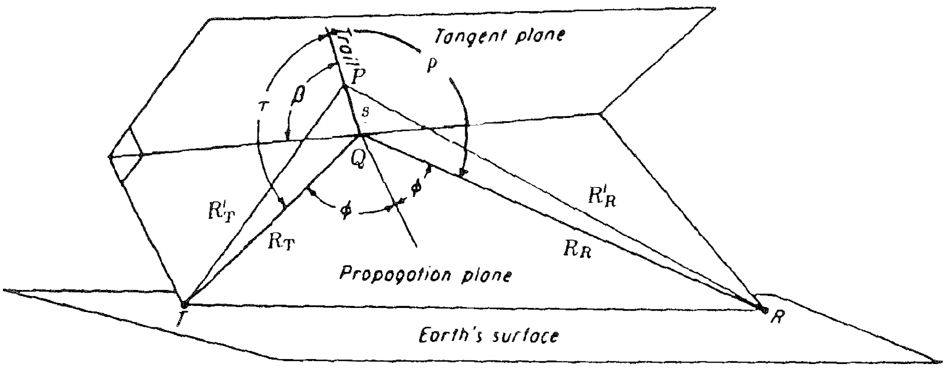

Figure 2: This figure shows some of the parameters discussed in the text. In this figure, Q is supposed to be the reflection point and P is an arbitrary point on the meteor trail.

and:

$$R_R' \simeq R_R + \cos\rho \cdot s + (\sin^2\rho/2R_R) \cdot s^2. \tag{5}$$

The specular point on the axis of the trail is the point P for which the total travel path $R_T' + R_R'$ of a radio wave scattered via P is minimal, and it may therefore be located by setting $\partial(R_T' + R_R')/\partial s$ equal to zero. If $s \ll R_T, R_R$, it is sufficient to retain in $R_T' + R_R'$ only those terms shown explicitly in (4) and (5), when differentiating, and the condition:

$$s = -(\cos\tau + \cos\rho)\,(\sin^2\tau/R_T + \sin^2\rho/R_R)^{-1} \tag{6}$$

is thereby obtained. The condition that the specular point should lie at the standard height h is obtained by setting $s = 0$ in (6):

$$\cos\tau + \cos\rho = 0, \tag{7}$$

which implies that τ and ρ are supplementary angles in such circumstances. In order to find the points $Q(x_0, y_0, z_0)$ at height h which are the reflection points of the trail through Q with direction cosines ξ, η, and ζ, we have to solve the system of equations (7), (8), (9), (10), (11), (12), and (1), where:

$$\cos\tau = \Big(\xi(x_0 + d/2) + \eta y_0 + \zeta(z_0 - A)\Big)/R_T, \tag{8}$$

$$\cos\rho = \Big(\xi(x_0 - d/2) + \eta y_0 + \zeta(z_0 - A)\Big)/R_R, \tag{9}$$

$$R_T = \sqrt{(x_0 + d/2)^2 + y_0^2 + (z_0 - A)^2}, \tag{10}$$

$$R_R = \sqrt{(x_0 - d/2)^2 + y_0^2 + (z_0 - A)^2}, \tag{11}$$

and:

$$z_0 = \sqrt{(R_E + h)^2 - x_0^2 - y_0^2} \tag{12}$$

are easy to derive. The system, however, is not so easy to solve. It leads to a polynomial equation of degree 6 in x_0 and y_0, which can only be solved numerically. This equation defines a relation between x_0 and y_0, giving rise to a curve in the horizontal plane. As pointed out in (Verbeeck, 1995), a well oriented trail will only yield a signal at the receiver

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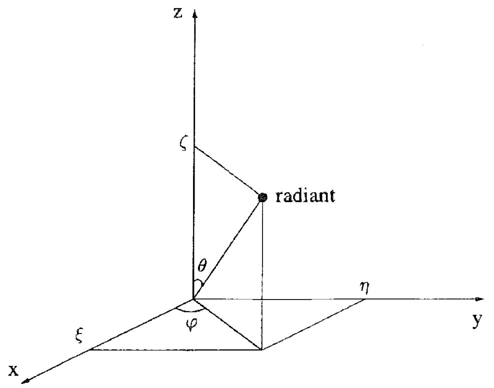

Figure 3: The spherical coordinates φ and θ.

if the reflection point lies above the horizons in T and R. This means we are looking for the sub-curve consisting of those points (x_0, y_0) of the curve that satisfy the additional inequalities (Verbeeck, 1995):

$$|x_0| \leq x_2 = -\frac{d}{2} + \frac{\sqrt{(R_E^2 - d^2/4)(h^2 + 2R_E h)}}{R_E},$$

and:

$$|y_0| \leq y_1(x_0) = \sqrt{-\frac{d^2+4A^2}{4A^2}x_0^2 - d\frac{d^2+4A^2}{4A^2}|x_0| + (R_E+h)^2 - \left(\frac{d^2+4A^2}{4A}\right)^2}.$$

The latter curve serves to indicate the regions from which specularly scattered signals *may* be expected. We denote the smallest and largest x_0-value from all points (x_0, y_0) on *this* curve by x_b respectively x_e and define y_b and y_e analogously. Of course, different curves will be obtained for different trail orientations. In Figures 4 to 6, some of these curves are drawn, assuming a distance $d = 1000$ km between T and R and a standard meteor height of 100 km. The curves are given for several values of the spherical coordinates φ and θ (see Figure 3). Note that the curve may possess several y_0-values for a given x_0 and vice versa. In the sequel we will drop the subscript 0 in x_0, y_0, and z_0.

3 Potentially observable trails

Equation (7) provides the condition for specular scattering at height h above the Earth's surface, whereas the ionized trails extend over a certain range of heights. Ideally, we would calculate some kind of observability function for each height h, and then integrate the result over h. Alas, the calculations for a fixed h are already very time-consuming, so we will deal with only one standard height h, and approximate the problem as follows. It will be assumed that the length L of a trail is proportional to $\sec Z$, where Z is the zenith distance of the meteor. This implies that all trails extend over the same height range, and corresponds to the theoretical conclusion (Herlofson, 1947) that the variation of ionization with height is independent of the orientation of the trail. Since reflection takes place whenever the reflection point is situated on the ionized trail, (7) may be violated to some extent without loss of the

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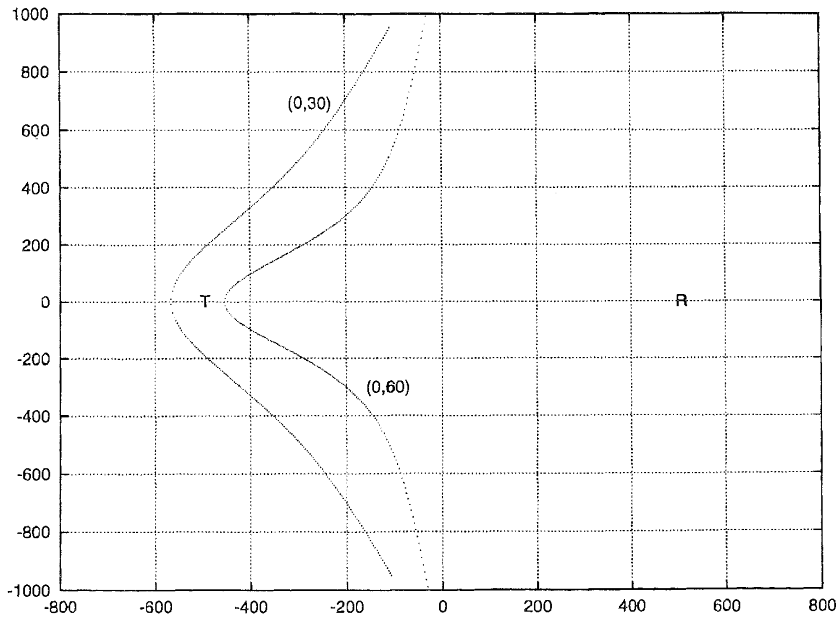

Figure 4: The $(s = 0)$-curve for $d = 1000$ km, $h = 100$ km, for the radiant positions $\varphi = 0°$, $\theta = 30°$ and $\varphi = 0°$, $\theta = 60°$.

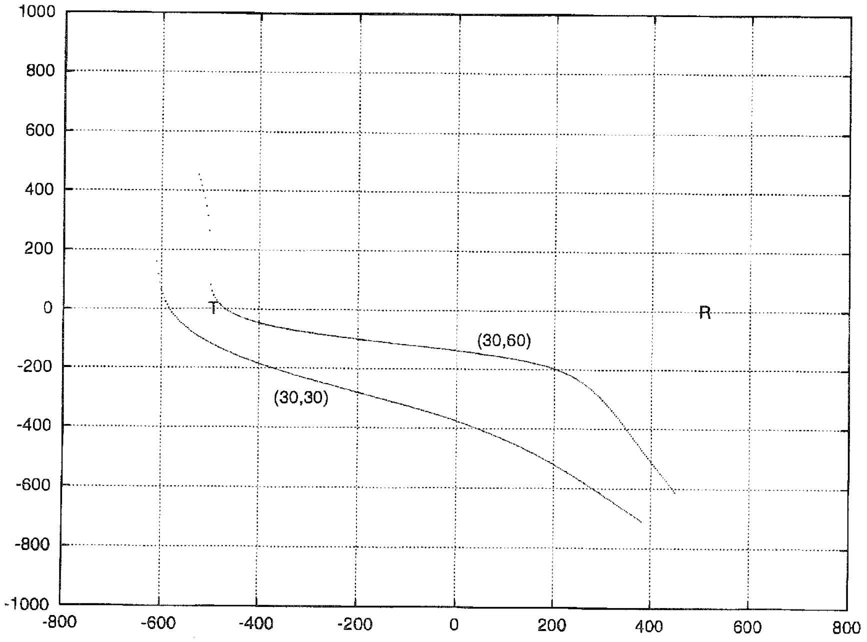

Figure 5: The $(s = 0)$-curve for $d = 1000$ km, $h = 100$ km, for the radiant positions $\varphi = 30°$, $\theta = 30°$ and $\varphi = 30°$, $\theta = 60°$.

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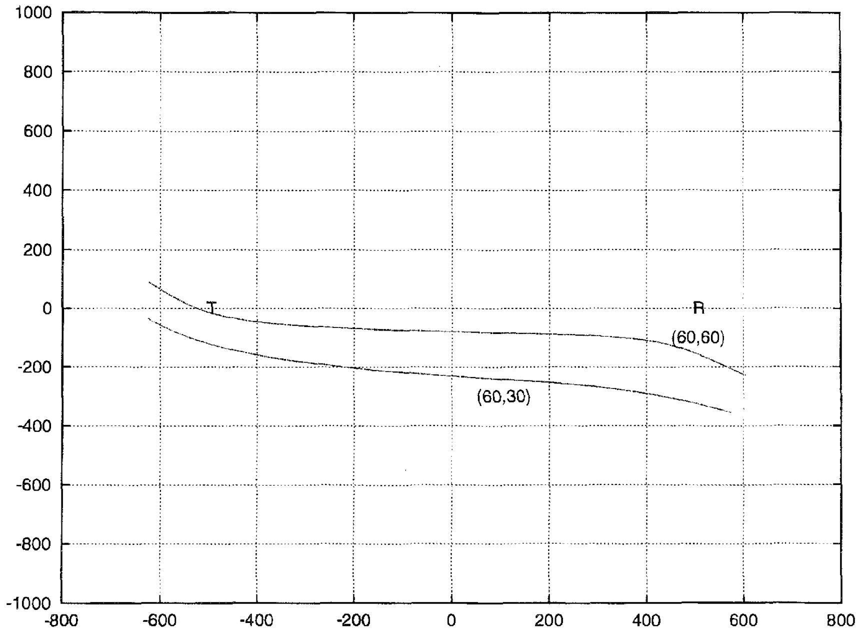

Figure 6: The $(s = 0)$-curve for $d = 1000$ km, $h = 100$ km, for the radiant positions $\varphi = 60°$, $\theta = 30°$ and $\varphi = 60°$, $\theta = 60°$.

specular process: reflection takes place as long as $-L/2 \leq s \leq L/2$. This implies that the curves of the previous section may be broadened into ribbons, while still representing the regions above which the trails must pass if they are to provide specularly scattered signals at R. These trails are called *potentially observable trails.*

To a first order approximation, the width w of the ribbon at a point on the curve will equal L divided by the horizontal gradient of s at that point.

The occurrence rate of potentially observable meteors $W_\sigma\, d\sigma$ which may be associated with an element of length $d\sigma$ along the $(s = 0)$-curve is proportional to $w \cos Z\, d\sigma$, with the factor of proportionality being dependent only on the incidence rate of meteors from the radiant direction concerned, which we suppose to be constant. The factor $\cos Z$ is a projection factor required because the ribbon does not lie perpendicular to the line of flight of the meteors (see Figure 7). All this entails:

$$W_\sigma d\sigma \sim \frac{L}{|\text{hor. grad. } s|_{s=0}} \cos Z d\sigma \sim \frac{d\sigma}{|\text{hor. grad. } s|_{s=0}}. \tag{13}$$

Differentiating (6), we get:

$$|\text{hor. grad. } s|_{s=0} = \frac{R_T R_R \sqrt{\left(\frac{\partial\chi}{\partial x}\right)^2_{s=0} + \left(\frac{\partial\chi}{\partial y}\right)^2_{s=0}}}{\sin^2\tau\,(R_T + R_R)}, \tag{14}$$

where $\chi = \cos\tau + \cos\rho$. Instead of considering intervals $d\sigma$ along the (s=0)-curve, we can consider intervals dx along the x-axis and replace the differential (13) by:

$$\frac{\sqrt{1 + \left(\frac{\partial y}{\partial x}\right)^2_{s=0}}}{|\text{hor. grad. } s|_{s=0}}\, dx = \frac{\sin^2\tau\,(R_T + R_R)}{R_T R_R |\frac{\partial\chi}{\partial y}|_{s=0}}\, dx, \tag{15}$$

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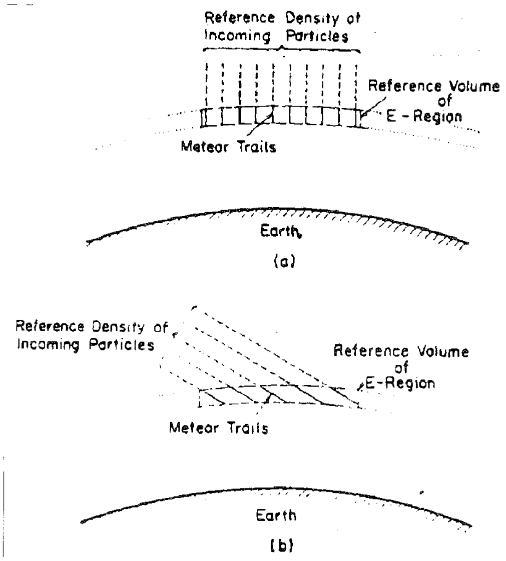

Figure 7: This figure illustrates why the meteor density per reference volume under a constant actual meteor rate is proportional to $\cos Z$, where Z is the zenith distance of the radiant.

or we can consider intervals dy along the y-axis and replace (13) by:

$$\frac{\sin^2\tau\,(R_T+R_R)}{R_T R_R|\frac{\partial\chi}{\partial x}|_{s=0}}\,dy. \tag{16}$$

Finally:

$$\frac{\partial\chi}{\partial y}|_{s=0} = \frac{(\eta-\zeta y/z)R_T - \cos\tau\, Ay/z}{R_T^2} + \frac{(\eta-\zeta y/z)R_R + \cos\tau\, Ay/z}{R_R^2}$$

and:

$$\begin{aligned}\frac{\partial\chi}{\partial x}|_{s=0} &= \frac{(\xi-\zeta x/z)R_T - \cos\tau\,(Ax/z+d/2)}{R_T^2} \\ &\quad + \frac{(\xi-\zeta x/z)R_R + \cos\tau\,(Ax/z-d/2)}{R_R^2}.\end{aligned}$$

4 Observable trails

If a meteor trail is potentially observable, it will reflect the signal from transmitter to receiver. However, it is possible that the amplitude of the received signal will be too weak to be detected by the receiver. A potentially observable meteor is actually *observable* if the amplitude A_R of the received signal is at least the minimal amplitude A_0 detectable by the receiver. The amplitude A_R is obtained by:

$$A_R = \sqrt{2rP_R}, \tag{17}$$

where P_R is the power received at R and r is the receiver input impedance. The received power profile $P_R(t)$ of an *underdense* meteor (i.e. a meteor with an electron line density well

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below 2.4×10^{14} m^{-1}, see e.g. (Wislez, 1996; McKinley, 1961); underdense meteors roughly correspond to meteors of magnitude +5 or fainter and constitute the bulk of the meteors observed by forward scatter) is given by (see (Verbeeck, 1996)):

$$P_R = \begin{cases} \frac{F P_T G_T G_R \lambda^3 r_e^2 \alpha^2 \sin^2\gamma \left(C^2(x(t))+S^2(x(t))\right)}{64\pi^2 R_T R_R (R_T+R_R)(1-\sin^2\phi\cos^2\beta)} \cdot \exp\left(\frac{-8\pi^2 r_0^2}{\lambda^2 \sec^2\phi}\right) & \text{if } t \leq 0 \\ \frac{F P_T G_T G_R \lambda^3 r_e^2 \alpha^2 \sin^2\gamma \left(C^2(x(t))+S^2(x(t))\right)}{64\pi^2 R_T R_R (R_T+R_R)(1-\sin^2\phi\cos^2\beta)} \cdot \exp\left(\frac{-8\pi^2 (r_0^2+4Dt)}{\lambda^2 \sec^2\phi}\right) & \text{if } t \geq 0. \end{cases} \quad (18)$$

In this formula, P_T is the transmitted power, G_T and G_R are the gains of, respectively, the transmitting and receiving antennas in the direction of the reflection point, λ is the wavelength to which the receiver is tuned, r_e is the classical radius of the electron ($2.817\,938 \times 10^{-15}$ m), α is the electron line density (considered constant throughout the meteor trail), γ is the angle between the electric vector of the incoming wave and the direction of the receiver at the reflection point, R_T and R_R are the distances of the reflection point to, respectively, the transmitter and the receiver, ϕ is the half forward scatter angle (i.e. half of the angle between the transmitter and the receiver at the reflection point), β is the angle between the meteor path and the propagation plane (i.e. the plane defined by transmitter, receiver and reflection point), r_0 is the initial radius of the ionized meteor trail near the reflection point, and D is the ambipolar diffusion coefficient near the reflection point. Time is denoted by t, and $t = 0$ when the meteoroid is at the reflection point. $C(x(t))$ and $S(x(t))$ are given by:

$$C(x(t)) = \int_{x_1}^{x(t)} \cos\frac{\pi x^2}{2}\, dx, \quad (19)$$

and:

$$S(x(t)) = \int_{x_1}^{x(t)} \sin\frac{\pi x^2}{2}\, dx, \quad (20)$$

where $x(t)$ is defined by:

$$x(t) = \sqrt{\frac{2(R_T + R_R)(1 - \sin^2\phi\cos^2\beta)}{\lambda R_T R_R}} \cdot s(t), \quad (21)$$

$s(t)$ being the distance of the meteoroid to the reflection point at time t. Please note this $x(t)$ bears no connection to the x_0 coordinate introduced in Section 2. If we suppose V to be constant and equal to the entry velocity V_∞, $s(t) = V_\infty t$. Finally, x_1 is the x-value corresponding to the starting point s_1 of the ionized trail of the meteor. For practical purposes, we can set $x_1 = -\infty$.

Due to the modulation of the radio signal, the transmitted power is distributed over a certain frequency range around the central frequency. For regular mono FM transmitters, the bandwidth of the signal is 150 kHz. As a consequence, receivers are designed with a sensitivity window of the same width. In general, several transmitters will transmit at least a part of their power within the sensitivity window of the receiver. Ideally, a transmitter transmits an equal amount of power throughout its full bandwidth, and the receiver is equally sensitive to all the frequencies in its frequency range. In this case, the received power is proportional to the width of the intersection of the frequency ranges of transmitter and receiver. This explains the factor F in (18), which is nothing but the quotient of the width of this intersection and the bandwidth of the transmitter.

I should remark that formula (18) assumes that the diffusion of the ionized trail is negligible before the reflection point is reached. For large heights, and hence strong diffusion, this is not a good approximation.

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We will suppose a potentially observable meteor is observable if its *maximal* received signal amplitude A_{Rmax} exceeds A_0. The maximum of $P_R(t)$ coincides more or less with the maximum of $C^2(x(t)) + S^2(x(t))$, i.e., $x(t_{max}) \simeq 1.2$, hence:

$$t_{max} \simeq \frac{1.2}{V_\infty}\sqrt{\frac{\lambda R_T R_R}{2(R_T + R_R)(1 - \sin^2\phi\cos^2\beta)}}. \quad (22)$$

If we retain in A_{Rmax} only those factors which are dependent on the transmitter, receiver, the position of the reflection point, or that of the radiant, we obtain $A_{Rmax} \sim K \cdot \alpha$, where:

$$K = \sqrt{\frac{rFP_TG_TG_R\lambda^3\sin^2\gamma}{R_TR_R(R_T + R_R)(1 - \sin^2\phi\cos^2\beta)}} \cdot \exp\Big(-\frac{4\pi^2(r_0^2 + 4Dt_{max})}{\lambda^2\sec^2\phi}\Big). \quad (23)$$

To find the fraction of the potentially observable meteors that is also observable, we have to calculate the probability $P(A_{Rmax} \geq A_0)$ that A_{Rmax} exceeds A_0. Since meteors of all masses have to be taken into account, we will need the mass distribution of the considered shower. The number of meteors $N(m)$ with a mass exceeding m is considered to be proportional to m^{1-s}, where s is the shower's mass index, *not* the curve parameter from Section 2. It is known that $\alpha \sim m\cos Z$, say $\alpha = a\,m\cos Z$ where a is a constant. Hence:

$$\begin{aligned} P(A_{Rmax} \geq A_0) &\sim P(\alpha \geq A_0K^{-1}) = P(a\,m\cos Z \geq A_0K^{-1}) \\ &= P(m \geq a^{-1}A_0K^{-1}\cos^{-1}Z) = N(a^{-1}A_0K^{-1}\cos^{-1}Z) \\ &\sim A_0^{1-s}K^{s-1}\cos^{s-1}Z. \end{aligned}$$

So $P(A_{Rmax} \geq A_0)$ is proportional to:

$$\begin{aligned} E &= \Big(\frac{rFP_TG_TG_R\lambda^3\sin^2\gamma\cos^2 Z}{A_0^2R_TR_R(R_T + R_R)(1 - \sin^2\phi\cos^2\beta)}\Big)^{\frac{s-1}{2}} \\ &\times \exp\Big(-\frac{4\pi^2(s-1)(r_0^2 + 4Dt_{max})}{\lambda^2\sec^2\phi}\Big). \end{aligned}$$

Now we are ready to define an observability function. It should be proportional to the number of meteor reflections observed when the real meteor activity is constant, and the constant of proportionality should be independent of the setup parameters and of the position of the radiant. For every interval dx on the x-axis between x_b and x_e, the occurrence rate of potentially observable shower meteors is proportional to (15). We obtain the occurrence rate of observable shower meteors by multiplying the latter expression with $P(A_{Rmax} \geq A_0)$. So if we integrate the product of (15) and E between x_b and x_e, we get a quantity proportional to the number of observed shower reflections. Hence, we define the Observability Function to be:

$$\int_{x_b}^{x_e} \frac{E\sin^2\tau\,(R_T + R_R)}{R_TR_R|\frac{\partial\chi}{\partial y}|_{s=0}}\,dx. \quad (24)$$

Equivalently, we can also define the Observability Function to be:

$$\int_{y_b}^{y_e} \frac{E\sin^2\tau\,(R_T + R_R)}{R_TR_R|\frac{\partial\chi}{\partial x}|_{s=0}}\,dy, \quad (25)$$

which ought to give the same result. Notice that the $(s = 0)$-curve may give several y-values for a given x-value and vice versa. The integrals (24) and (25) are taken over each of these y-values for a given x and vice versa, meaning integration takes place over the entire curve.

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5 Discussion

In section 4 we defined an "Observability Function." In 1958, Hines (Hines, 1958) already defined an Observability Function, which was the basis for the present (different!) one. However, Hines neglected a lot of parameters when evaluating the maximal received power P_R, the most important of which is probably the exponential factor. This is expected to give significant differences. Also, Hines implicitly assumes the mass index equals 2.

In 1987, Steyaert wrote the program FORWARD to calculate yet another (though related) Observability Function (Steyaert, 1987a; Steyaert, 1987b). Although more or less the same ideas are incorporated into his program, his Observability Function is less accurate than the other two. There are several reasons for this: amongst other things a flat Earth is assumed, the meteors are supposed to have their reflection point at a fixed height h instead of permitting a height interval, and the magnitude distribution (poorly known for the faint underdense meteors!) rather than the mass distribution is used.

Since it takes into account more parameters, the present Observability Function should describe the sensitivity of a forward scatter setup for underdense shower meteors in a better fashion than the other two observability functions. At present, I am writing a program to calculate this Observability Function, but it is still far from completion. I will discuss it and compare the results with the other observability functions in a future paper. Basically, if a meteor shower and a date and time are given, we should be able to calculate the azimuth and elevation of the radiant and transform these data into the coordinate system used in the present paper. Then we should find the points of the ($s = 0$)-curve and calculate the Observability Function with (24) or (25). If desired, we can normalize the result (in a standard way!) if we do not like its magnitude.

This program could be used to correct raw forward scatter underdense meteor rates to give a better measure for meteor shower activity by dividing them by the Observability Function. Of course, this only holds if the sporadic background and the contamination by other showers is small or removed. If all parameters discussed in the text are incorporated, the corrected rates from one system should be comparable to those of another system (in theory, that is). However, some of these parameters are difficult to find, for example the gains G_T and G_R. If some parameters concerning the transmitter or receiver are unavailable, it is still possible to compare corrected rates for different observations with the *same* setup by setting the unknown parameters equal to some standard value. However, parameters depending on the position of the reflection point, such as G_T and G_R, are absolutely essential for useful results. In fact, this is probably why Steyaert's FORWARD did not prove very useful in correcting observed rates: it assumes $G_T = 1$. If different transmitters lie within the receiver's frequency band, the Observability Functions for these transmitters simply have to be added to obtain the total Observability Function.

6 Conclusion

We have defined an Observability Function which is proportional to the number of *underdense* shower meteors detected by a forward scatter setup under given (input) conditions, and assuming a constant actual meteor rate. It is given by (24) or, alternatively, by (25). Currently, I am writing a program to calculate this Observability Function. In a future paper

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I will describe the program and how to use it. It is expected that forward scatter meteor rates corrected with the Observability Function will allow a much better interpretation of shower activity, and (in theory) even a comparison of observations by different forward scatter setups. To obtain these goals, however, one must know the values of many setup parameters.

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