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RADAR OBSERVATIONS OF ASH ERUPTIONS

By DAVID M. HARRIS, WILLIAM I. ROSE, JR.[1], ROBERT ROE[2], *and* MARTIN R. THOMPSON[3]

ABSTRACT

Radar systems located at Portland, Oreg., Seattle, Wash., and near Spokane, Wash., have been used extensively for observations of ash clouds from explosive volcanic eruptions at Mount St. Helens during 1980. Eruption clouds are composed of silicate particles and are therefore detectable by radar. Radar observations can be made at night and in overcast weather when conventional observations of eruptions are difficult.

Radar observations show that the May 18, 1980, eruption lasted about 9 hr and had a column height of at least 14 km relative to sea level for most of the period. During the eruption, there were four periods of increased column height, which correlated with the appearance of individual, dense ash clouds shown on the radar plan position indicator (PPI) screen. The examples of radar observations described here demonstrate the potential of radar for measuring the heights of eruption columns, determining the duration of eruptions, and determining the direction and rates of ash cloud movements downwind from the volcano. If the particle size distribution within an ash cloud is known or can be estimated, then radar observations may, in principle, provide the additional data required to estimate the mass of ash suspended in the cloud and potential ash-fall amounts over specified areas.

INTRODUCTION

Public safety could be enhanced if the locations, times, and amounts of potential ash fall could be accurately predicted during an eruption. The need for a rapid, remote-sensing method and a sound scientific basis for inferring the amount of volcanic ash that is in the atmosphere downwind from a volcano is obvious. The purpose of this paper is to illustrate the theory and application of radar to volcanic-ash clouds. Our understanding of ash-fall processes and our abilities to forecast ash fall may increase as a result of radar observations of ash clouds.

The use of radar to observe ash eruptions and to track ash clouds away from their sources is a new and significant area for volcanological research. Johnston (1978) cited radar measurements made in Alaska during eruptions of Augustine volcano in January 1976. Radar measurements of eruption column heights over Augustine were made at the National Weather Service (NWS) office in King Salmon, Alaska, and at Sparrevohn Air Force Base, apparently the first radar observations of airborne volcanic ash in the United States. In March 1980, David Johnston advised the NWS in Portland and Seattle that weather surveillance radar might be used to observe the growth, width, tops, and movement of major eruption clouds from Mount St. Helens. Two of the authors (Rose and Harris) also made requests for radar observations of ash clouds and eruption column heights without knowledge of Johnston's earlier discussions with NWS personnel, all of which led to the joint effort by the NWS and USGS reported here.

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DETECTION OF VOLCANIC ASH BY RADAR

The minimum concentration of volcanic ash required for detection by radar is a function of the physical parameters of the particular radar system, the size distribution and concentrations of particles in the ash cloud, and the distance between the radar source and the cloud.

THE RADAR EQUATION FOR DISTRIBUTED TARGETS

Volcanic-ash clouds are similar to thunderstorms as radar targets. Ash clouds and thunderstorms cause backscatter of some of the energy that is incident on their constituent ash particles or raindrops. Particle fallout from ash clouds may involve the growth of ash particles by coalescence of smaller ones, a physical process that is also important in rainfall. Also, thunderstorms and ash clouds are large compared to the volume occupied by one pulse of the radar. Thus, the theory governing radar reflections from meteorological targets (such as thunderstorms) may be applied to radar reflections from ash clouds.

The development of theory governing radar reflections from randomly distributed targets (such as thunderstorms) was summarized by Probert-Jones (1962). He found errors in previous theoretical radar equations, produced a mathematically correct version, and showed that radar observations agreed with the new equation within the limits of experimental error.

Probert-Jones's (1962) expression for the received power (P_r) from a target composed of randomly distributed particles is

$$P_r = \frac{\pi^3}{16 \ln 2} \frac{P_o h}{\lambda^2} \frac{G^2 \theta \phi}{R^2} \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2 \Sigma r^6 , \tag{1}$$

where P_r = received power
P_o = peak transmitted power
h = radar pulse length in space (distance)
G = actual gain of antenna
θ = horizontal beam width to the -3 dB level for one-way transmission
ϕ = vertical beam width to the -3 dB level for one-way transmission
ϵ = dielectric constant of spherical particles
λ = wavelength
R = range
r = radius of spherical particles.

The summation, Σr^6, is taken over all the particles of various sizes in a unit volume of target space. Equation 1 above is valid when the target completely fills the beam as defined by θ, ϕ, and h at a particular range R. The actual gain, G, is the antenna gain along the beam axis relative to an isotropic radiator. The gain is related to the beam widths by

$$G = \frac{\pi^2 k^2}{\theta \phi} , \tag{2}$$

where k is a factor that corrects for the nonuniformity of illumination of the antenna (Probert-Jones, 1962); k is approximately unity for antennas of circular cross section.

Equation 1 includes four variables in addition to those specific to a particular radar system. The terms P_o, h, λ, G, θ, and ϕ are radar-system parameters and are constant for a particular radar system. The term, $|(\epsilon - 1)/(\epsilon + 2)|^2$, depends upon the dielectric constant (ϵ) of the particles. The term, Σr^6, depends upon the size distribution and number density of the particles in the target. The term, $1/R^2$, depends upon the distance (range) between the radar system and the target. The term for received power, P_r, is a function of all of the above. Therefore, for a particular radar system, the variables in the radar equation are Σr^6, $1/R^2$, ϵ, and P_r. A solution can be obtained if three of the variables are known.

REFLECTIVITY OF ASH CLOUDS

REFLECTIVITY

The reflectivity of a radar target is a function of the abundance of particles and their scattering cross sections within the target. The reflectivity, η, is the summation of the backscatter cross sections of the particles per unit volume averaged over the radar pulse volume (Atlas, 1964). For solid spherical particles which obey Rayleigh scattering, the reflectivity is equal to:

$$\eta = \frac{2^6 \pi^5}{\lambda^4} \cdot \left| \frac{\epsilon - 1}{\epsilon + 2} \right|^2 \cdot \Sigma r^6 \qquad (3)$$

The reflectivity, η, does not appear explicitly in equation 1, but the dependence of the reflectivity upon the particle-size distribution, number density, and dielectric constant and wavelength are evident by comparing equations 1 and 3. The dielectric constant, ϵ, is that of the void-free silicate glass and (or) crystals.

REFLECTIVITY FACTOR

The reflectivity factor, Z, is a parameter of the radar target; it is equal to $\Sigma(2r)^6$, the summation of the sixth-power of the particle diameter for all of the particles in a unit volume of target space. The conventional units for Z are mm^6/m^3 (Atlas, 1964).

EFFECTS OF PARTICLE SHAPE ON REFLECTIVITY

In the case of volcanic-ash clouds, it is necessary to consider what effects, if any, the presence of voids and the occurrence of nonspherical particle shapes will have on the reflectivity. It has been shown (for instance, Atlas, 1964) that in relation to hail, enlarging an ice particle and filling voids in the particle with air changes the density, diameter, and dielectric factor in such a way that the particle's contribution to the reflectivity is unchanged. This argument also applies, by analogy, to vesicular silicate glass.

Studies of backscatter for nonspherical particles (see review in Atlas, 1964) show that the reflectivity varies as the particle shapes become more distorted from that of a sphere, as the refractive index increases, and as the orientations of the particles within a population become less random. Preferred orientation of aspherical particles may increase or decrease the reflectivity, depending upon how the long axes of the particles are alined relative to the direction of polarization of the radar wave. For a population of angular glass shards of various shapes and probably no preferred orientation within an ash cloud, the increase or decrease in reflectivity is probably small. Because the largest ash particles tend to be equant (Rose and Hoffman, 1980 and 1981) and because these make the largest contribution to the total reflectivity, failure to make corrections for the angular shapes of glass shards in the smaller size ranges probably is not significant.

RADAR TARGET PARAMETERS FOR ASH AND RAIN

Radar target parameters calculated for an ash cloud that was sampled by a research aircraft (Rose and others, 1980) are compared in table 31 with analogous parameters for warm orographic rain and thundershowers. The comparisons are helpful in determining whether such an ash cloud should be detectable by radar. Radar target parameters for the ash cloud are most similar to those for warm orographic rain even though their reflectivities differ by an order of magnitude. However, because the reflectivity factor depends on the sixth power of the particle diameter and on the number density of particles, the reflectivity factor for the ash cloud would increase nearly an order of magnitude (by a factor of 8) if the particle diameters were increased from 0.15 to 0.22 mm. Furthermore, the greater refractive index factor, $|K|^2 = |(\epsilon - 1)/(\epsilon + 2)|^2$, for the ash particles as compared to the raindrops (0.36 versus 0.197) enhances the detectability of an ash target by nearly a factor of 2, relative to a rain target with identical particle size distribution and number density. Radar detection of volcanic ash would be further enhanced if there were either a larger number of density particles or larger particle diameters in the ash cloud compared to those shown in table 31.

Table 31.—Comparison of radar target parameters for orographic rain, thundershowers, and volcanic ash

[Ash-fall parameters from Rose and others (1980) and from this study; orographic rain parameters from Blanchard (1953); thundershower parameters from Jones (1956) and Atlas and Chmela (1957)]

Radar target parameters	Ash fall (Fuego volcano, Guatemala)	Warm orographic rain[2] (Hawaii)	Thundershowers (Illinois)		
			Light	Moderate	Heavy
Ash-fall or rainfall intensity (mm/hr)---------	Light	0.02	0.016	6	21
Particle concentration or liquid water content (g/m^3)----------	0.04	0.05	0.0009	0.3	1.0
Particle diameter (mm)------------	0.15	0.22	1.2	1.4	1.7
Number density (per m^3)--------	$8.7x10^3$	$3.6x10^4$	1.0	210	390
Reflectivity factor (mm^6/m^3)--------	0.1	2.0	5.0	$3.4x10^3$	$1.4x10^4$
Refractive index factor, K^2----	0.36	0.197	0.197	0.197	0.197

Also, for a given concentration and size distribution of silicate particles in a target, the reflectivity of an ash cloud varies inversely with the fourth power of the radar wavelength used. Therefore, the wavelength is an important consideration when evaluating the suitability of a particular radar system for observations of volcanic ash. On the basis of these comparisons, we can expect that detection of volcanic ash for the conditions shown in table 31 would be similar to radar detection of orographic rain, particularly because of similarities of particle diameter and particle concentrations.

DESCRIPTION OF RADAR SYSTEMS

The eruption of Mount St. Helens on May 18, 1980, was observed on three radar systems. Ash clouds were tracked on Federal Aviation Administration (FAA) radar systems located at Seattle and near Spokane, Wash. In addition, the NWS radar system at Portland, Oreg., was used to measure the height of the eruption column directly above Mount St. Helens. Although the locations and specifications for all three radar systems are given in table 32, only data obtained from the Portland and Seattle radar systems were used for quantitative calculations in this paper; data from Spokane were used only for qualitative tracking of the ash cloud.

The radar systems at Portland (NWS) and Seattle (FAA) differ greatly in peak transmitting power, vertical beam width, and wavelength. The 6.2° vertical beam width of the Seattle radar precludes its use for measurement of vertical dimensions of ash clouds, but the Portland radar is ideal for this purpose. The greater peak power of the Seattle radar as compared to that of the Portland radar does not result in a large advantage for the system because of the attenuating effects of the longer wavelength, shorter pulse length, and larger vertical beam width, all of which reduce the power received from a given target. Both systems have the capability for operation in contour-logging mode. In this mode, the power received from a target is measured, corrected for the $1/R^2$ range attenuation, and compared to particular reference levels. Then the selected levels are displayed on the radar's plan position indicator (PPI) and range height indicator (RHI) screens. This mode contrasts with ordinary operation in which the PPI and RHI screens display the images of the detected targets without regard to signal strength.

Attenuation of the radar beam by intervening rainfall was not a major problem because clear weather prevailed for the May 18, July 22, August 7, and October 16–18 eruptions. However, we can evaluate the significance of attenuation by rainfall for radar observations of ash clouds. Atlas (1964) reviewed observations and theory on attenuation of radar signals by snow and rain. The amount of attenuation depends on

Table 32.—Specifications of radar systems

[NWS, National Weather Service; FAA, Federal Aviation Administration; kW, kilowatts; dBm, decibels below milliwatts; W, watts]

Nearest city-------	Portland, Oreg.	Seattle, Wash.	Spokane, Wash.
Agency-------------	NWS	FAA	FAA
Lat N.-------------	45°36'	47°34'	47°34'
Long W.------------	122°36'	122°25'	117°05'
Radar parameters:			
Peak transmitted power (kW)------------------	230	5,000	5,000
Horizontal beam width (degrees)--------------	1.65	1.35	1.3
Vertical beam width (degrees).-------------	1.65	6.2	22
Pulse Length:			
(time,)s)--------------	3	2	6
(distance, km)---------	0.9	0.6	1.8
Wavelength (cm)----------	5	23	23
Sensitivity:			
(dBm)------------------	103	111	111
(W)--------------------	$5x10^{-14}$	$8x10^{-15}$	$8x10^{-15}$
Pulse rate (per s)-------	259	360	Not known.
Maximum range (km)-------	400	400	400

the wavelength, raindrop size distribution and concentration, and path length through rainfall. For the radar system wavelength at Portland (5 cm), attenuation by rain is more important than for those operating at longer wavelengths (for example, 23 cm at Seattle). The rainfall attenuation coefficient per unit rainfall rate (mm/hr) for one-way transmission at a wavelength of 5 cm is about 0.003 (dB/km)/(mm/hr) (Wexler and Atlas, 1963). For example, the amount of attenuation expected from a 2-mm/hr rainfall rate and a 100-km pathlength is about 0.6 dB, or about a 15 percent reduction of power. Attenuation by rainfall would be a possible source of error in Portland radar observations of Mount St. Helens when rain is present along the path.

MEASUREMENTS OF ASH-CLOUD DIMENSIONS

An important question is whether radar observations can be used to measure ash-cloud dimensions. A thorough discussion of radar measurements of storm dimensions is given in Atlas (1964). The horizontal dimensions of radar-detected ash clouds from the May 18 eruption exceeded the horizontal beam width of the Seattle radar. The maximum reflectivity of typical ash clouds (at a constant range) downwind from Mount St. Helens on May 18 corresponded to a level 2 in the contour-logging mode (reflectivity equivalent to that due to stratiform rainfall intensities of 2.5–12.5 mm/hr). However, within the eruption column over the volcano, the maximum reflectivity observed corresponded to a level 4 (reflectivities equivalent to those due to stratiform rainfall intensities of 25–50 mm/hr). The observed ranges in reflectivity in eruption columns and ash clouds from Mount St. Helens are less than those of severe storms, and therefore, accurate measurements of ash-cloud dimensions are possible. False echoes (spurious reflections) caused by radiation from the side lobes of the antenna beam, which could have indicated erroneous column heights, have not been detected. Furthermore, our observations of eruption columns show that the reflectivity decreases rapidly near the radar-detectable tops. Column heights were measured with the Portland radar and have been corrected for curvature of the Earth and for beam width; the latter correction involved subtraction of one-half beam width. The degree of correspondence between the visible boundary of an ash cloud and its boundary as detected by radar is not known.

RADAR OBSERVATIONS OF THE MAY 18 ERUPTION

ASH EMISSION AT MOUNT ST. HELENS

The May 18 eruption began at 0832 PDT, and the Plinian eruption column which resulted was observed on radar. The height of the eruption column (directly above Mount St. Helens) was measured at the Portland NWS office from 0900 to 2200 PDT (fig. 190). The height of the eruption column exceeded 14 km (relative to sea level) for most of the eruption, 9 hr, and the maximum reflectivity level observed for the column varied from 2 to 4 during the eruption. Periods of increased column height generally correlated with increased reflectivity, especially between 0840 and 0900 PDT, and from 1030 to 1230, 1330 to 1400, and 1600 to 1700 PDT.

Particle-size studies of the May 18 ash indicate a multimodal distribution, with size peaks at 90, 25, and 10 μm (Rose and Hoffman, 1980, 1981; Sarna-Wojcicki, Shipley, and others, this volume). Terminal velocities would have been too slow for the fine particles to have settled individually, and they probably fell as composite particles of about 90 μm in diameter, possibly enhancing the radar reflectivity of the ash cloud. Sulfate coatings on ash particles (Rose, 1977; Rose and others, 1980; Nehring and Johnston, this volume) probably were too minor during the May 18 eruption to have significantly influenced the radar reflectivity.

TRACKING OF ASH CLOUDS

At hourly intervals on May 18, Martin Thompson traced the radar images of ash clouds as displayed on the radar PPI screens of the Seattle and Spokane radar systems. (These radar systems are operated remotely by the FAA Seattle Air Route Traffic Control Center in Auburn, Wash.) Thompson's tracings are composites from the two radar systems and are shown in figure 191. The horizontal boundaries of the ash plume, as seen in National Oceanic and Atmos-

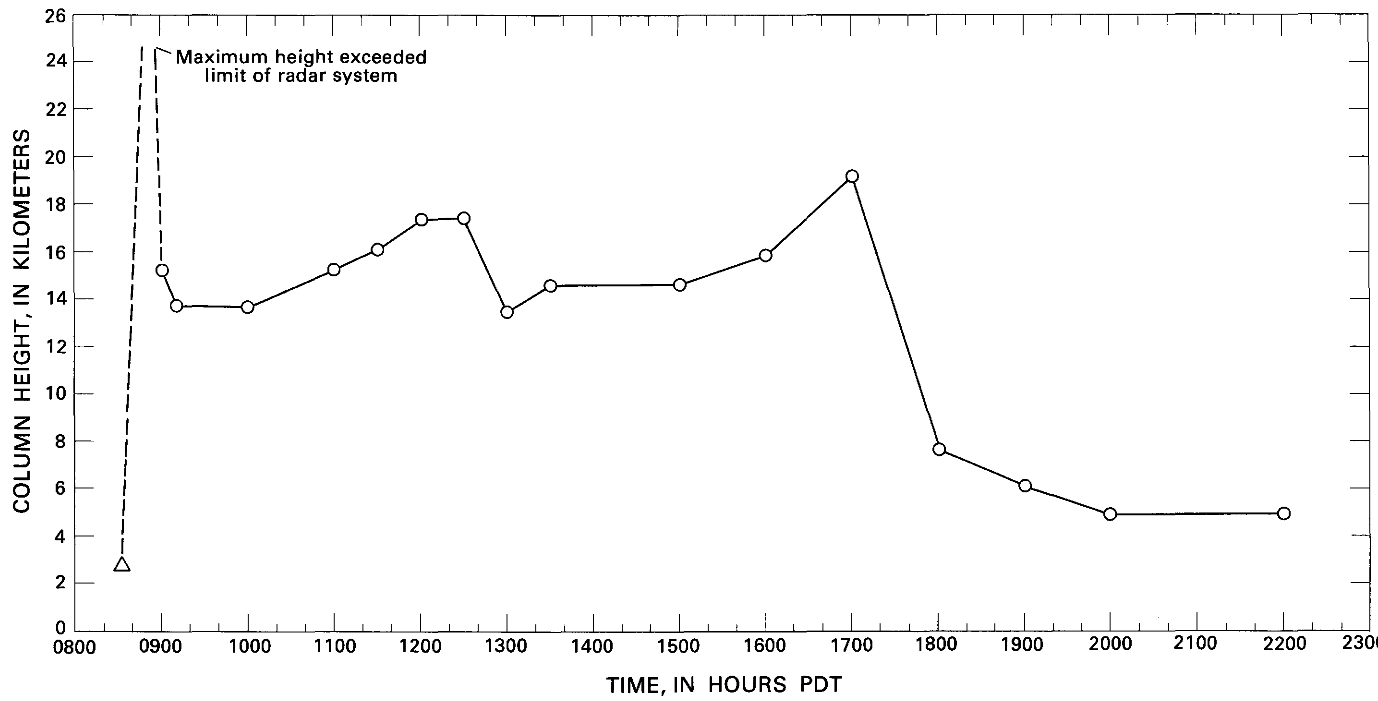

Figure 190.—Heights of the May 18 Plinian eruption column near Mount St. Helens, as determined by Portland radar. Heights are relative to sea level. Base value (triangle) is plotted at time eruption began and at approximate altitude of vent; it is followed by an unmeasurable value (connected approximately by a dashed line).

pheric Administration (NOAA) satellite images, are also shown. The satellite images reveal the overall shape of the entire cloud and of the high-altitude ash trajectory, whereas radar pulses penetrate the ash clouds and are partly reflected by particles within the dense cores of ash clouds. The radar-detectable ash clouds were mostly within the broad plume shown on satellite images.

The radar images in figure 191 show details of the shape of the denser portions of the eruption cloud at hourly intervals. Several of the images show more than one discrete ash cloud (for example, images from 1340 and 1440 PDT). Successive appearances of these discrete ash clouds near the volcano correlate with increases in column height and, we believe, reflect increases in the eruption rate (for example, fig. 190 and table 33). The times of increased column height (eruption rate) (beginning at approximately 0845, 1015, 1245, and 1600 PDT) are interpolated from figure 191 to the nearest quarter hour because we do not have a continuous record of ash-cloud sizes and column heights. The data are sufficient, however, to demonstrate that the column height and therefore the eruption rate varied substantially during the 9-hr eruption.

DIMENSIONS OF THE INITIAL ASH CLOUD

The plan area of the initial ash cloud, as detected by radar, appeared largely unchanged from 0940 to 1040 PDT; however, the plan area increased from 1040 to 1140 PDT as the ash cloud moved farther from Mount St. Helens volcano and began to be tracked on the Spokane radar system. The initial ash cloud contained much of the ash erupted in the Plinian column at Mount St. Helens from about 0832 to 0900 PDT on May 18. The portion of the cloud from which level-1 radar echoes could be detected on the Seattle radar, as measured at 1040 PDT, had a plan area of 4,900 km^2. The range between Seattle and the center of the cloud was about 190 km. At the ash-cloud location, the vertical beam width (from the Seattle radar) would have been about 20 km and the horizontal beam width would have been about 4.6 km. The ash-cloud thickness is not known, but is estimated to have been about 12 km. Thus, the ash cloud may only have intersected about 60 percent of the radar pulse volume. However, correcting for this is not justified because the ash-cloud thickness and variation of reflectivity as a function of height within

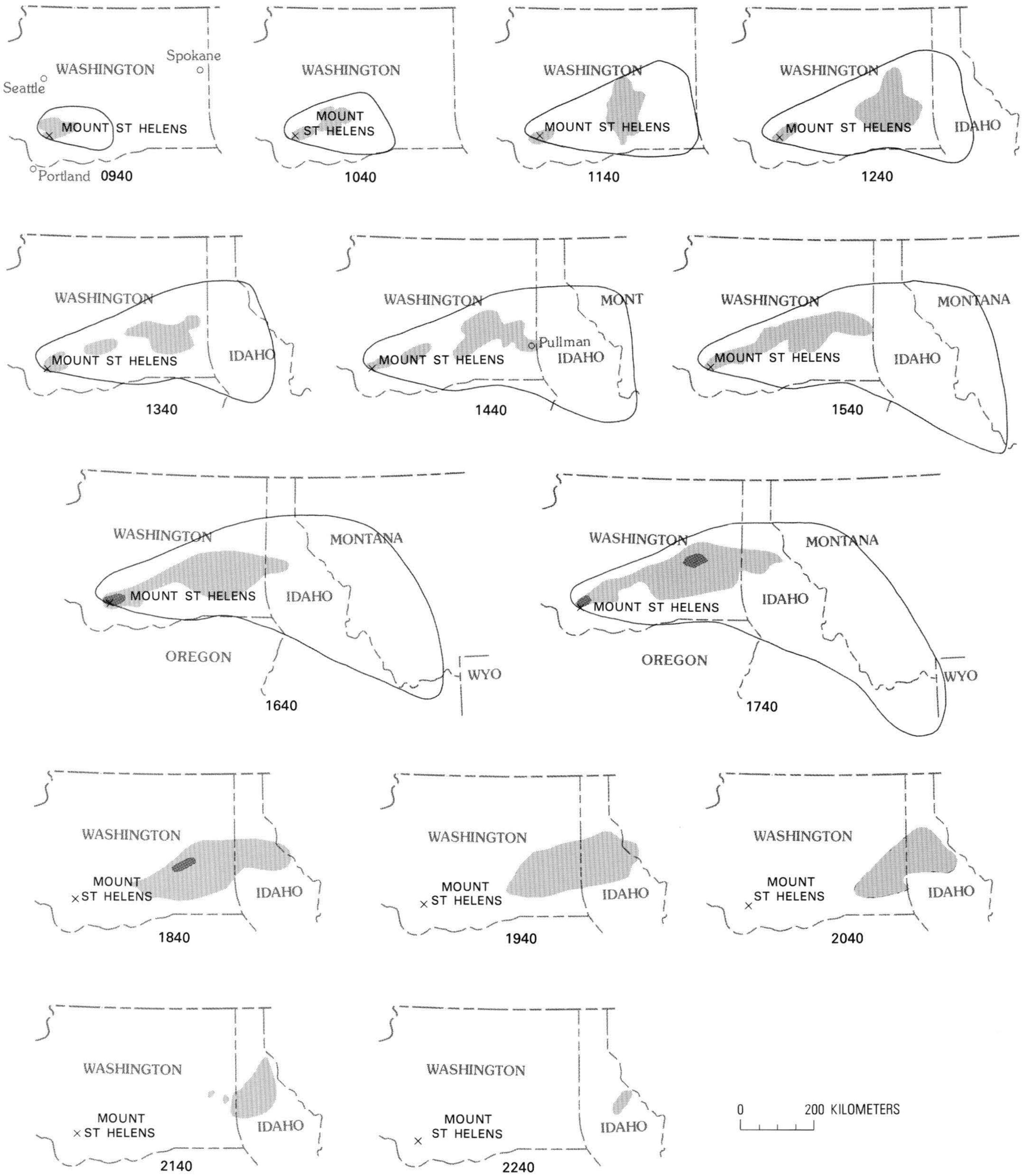

Figure 191.—Shape and structure of the May 18 eruption cloud from Mount St. Helens (X), as depicted by Seattle and Spokane radar systems and NOAA weather satellite. The solid line outlines the whole ash cloud, as seen in the satellite images. Hourly tracings of radar reflections of level 1 are shown as light patterned areas; level-2 reflections are shown as dark patterned areas. Time is shown in PDT.

Table 33.—Estimates of magma eruption rates on May 18 using radar measurements of Plinian column heights

[Calculations based upon the formulae, $H = 8.2 \times Q^{0.25}$, and $\dot{Q} = \sigma \dot{V} s (\theta - \theta_A) F$, of Wilson and others (1978), where H = measured column height above vent, $\dot{Q}$ = steady-state release of thermal energy, σ = density of dacite (2500 kg/m³), s = specific heat of dacite (1.1×10^{-3} joules/kg.deg), θ = magmatic temperature of dacite (1200 K), θ_A = air temperature (300 K), and F = 0.9 (an efficiency factor)]

Time of measurement (PDT)	Column height above vent, H (km)	Eruption rate of dense dacite, $\dot{V}$ (10^3 m^3/s)
≈0845	22	23.0
0915	12	2.0
0938	12	2.0
1100	13	2.8
1158	15	5.0
1255	11	1.5
1330	13	2.8
1500	13	2.8
1605	14	3.8
1705	17	8.3
1800	5	0.06

the ash cloud were not measured. The estimated volume of the radar-detectable ash cloud is 5.9×10^4 km³.

METHOD FOR ESTIMATING POTENTIAL ASH FALL

THE FIRST ASH CLOUD FROM THE MAY 18 ERUPTION

The volume of airborne volcanic ash, and therefore the potential ash fall, depends on the plan area, the vertical thickness, and the mean particle concentration of the ash cloud. The most reliable radar data for estimates of ash volume are likely to be those obtained before substantial amounts of particle coalescence and ash fall occurred, because the particle-size distributions within clouds during ash fall are not known. If a substantial amount of particle coalescence has not occurred, then the particle size distribution within an ash cloud may be approximated by the size distribution of air-fall ash for the eruption. These considerations suggested that the 1040 PDT image (Seattle radar) of the first ash cloud was the best one for which a crude estimate of potential ash fall might be made.

REFLECTIVITY FACTOR INFERRED FROM RADAR OBSERVATIONS

The minimum value of the reflectivity factor (Z) required for detection of the ash cloud was determined from the radar equation 1, the antenna gain equation 2, the range ($R = 190$ km) to the center of the ash cloud, and the parameters for the Seattle radar system (table 32). We assumed that the power received (P_r) from the radar-detected ash cloud was equal to the detection limit (8×10^{-15} W) of the radar system. The dielectric constant (ϵ) of the silicate particles (mostly dacitic glass) from Mount St. Helens was assumed to be 5.5 for the wavelength (23 cm) of the Seattle radar. Campbell and Ulrichs (1969) measured the dielectric constant of obsidian from Newberry caldera, Oregon, and obtained a value of 5.5 for a wavelength of 8.6 cm. The minimum value of the reflectivity factor for the ash cloud is 8.5 mm⁶/m³. The minimum reflectivity factor inferred for the May 18 ash cloud (0832–0900 PDT) exceeds those shown in table 31 for warm orographic rain and light thundershowers.

PARTICLE CONCENTRATION INFERRED FROM REFLECTIVITY FACTOR

The silicate-particle concentration of the ash cloud can be inferred from the reflectivity factor ($Z = \Sigma (2r)^6$), if the size distribution of particles in the ash cloud is known.

PARTICLE-SIZE-DISTRIBUTION MODEL

The silicate-particle concentration in the cloud can be estimated for a particle-size-distribution model that approximates the measured size distribution of the May 18 air-fall ash in eastern Washington. We modeled the particle-size distribution in the ash cloud by assuming that 25 percent (by weight) of the ash particles were spheres of diameter 150 μm, 50 percent were spheres of diameter 100 μm, and 25 percent were spheres of diameter 30 μm.

REFLECTIVITY FACTOR PER UNIT MASS OF ASH

The reflectivity factors per unit mass of ash (for each particle size) are 2.57 mm⁶/g (150 μm), 0.764 mm⁶/g

(100 μm), and 2.06×10^{-2} mm⁶/g (30 μm). The weighted value of the reflectivity factor per unit mass for the model size distribution is 1.0 mm^6/g. The relative contributions of the three ash sizes to the total reflectivity factor are 62.4 percent, 37.1 percent, and 0.5 percent, respectively.

PARTICLE CONCENTRATION IN THE ASH CLOUD

The inferred concentration of silicate particles in the ash cloud, using the observed reflectivity factor and the particle-size-distribution model, is $8.5\ mm^6/m^3 / 1.0\ mm^6/g = 8.5\ g/m^3$. This represents the concentration of ash in the first ash cloud downwind from Mount St. Helens, 1.5–2 hr after it was erupted.

POTENTIAL ASH-FALL MASS AND VOLUME

The potential ash-fall mass can be calculated from the volume (5.9×10^4 km^3) of, and the concentration of silicate particles (8.5 g/m^3) in, the radar-detected part of the ash cloud. The calculated mass of ash is 5.0×10^{14} g. Similarly, the potential ash-fall volume is about 0.20 km^3, for a particle density of 2.5 g/cm^3. These estimates represent the mass and volume of ash remaining in the first ash cloud downwind from Mount St. Helens, 1.5–2 hr after it was erupted.

ESTIMATES OF POTENTIAL ASH FALL

In theory, the potential ash fall from the radar-detected part of the ash cloud can be estimated. The ash cloud, as detected by radar, was about 70 km wide and it traveled in an east-northeasterly direction at about 135 km/hr. The minimum potential ash-fall area (km^2) and mean amount of ash (mm) could be estimated if either the duration of ash fall from the cloud or the ash-fall intensity (mm/hr) is known. The ash-fall intensity is the more important of the two parameters because it might be used, along with the quantities inferred from radar, to forecast the duration and the mean ash-fall amounts over the potential ash-fall area. Table 34 illustrates one procedure that might be used to estimate, in retrospect, the ash-fall intensity from the radar-detectable part of the initial ash cloud downwind from Mount St. Helens. The calculated ash-fall intensity is 13 mm/hr and it

Table 34.—Ash-fall intensity estimated from physical characteristics inferred for the initial ash cloud of the May 18 eruption

Particle diameter[1] (μm)	Mass fraction of ash in cloud[1]	Concentration of ash in cloud[2] (g/cm^3)	Total mass of particles in ash cloud[3] (g)	Calculated terminal velocity[4] (cm/s)	Calculated ash-fall intensity[5] (mm/hr)
150	0.25	2.1×10^{-6}	1.25×10^{14}	70	5.3
100	0.50	4.3×10^{-6}	2.5×10^{14}	48	7.4
30	0.25	2.1×10^{-6}	1.25×10^{14}	5	.4
Totals---	1.00	8.5×10^{-6}	5.0×10^{14}		13.1

[1]From particle size-distribution model described in text.

[2]Minimum concentration inferred from radar observations and particle size-distribution model.

[3]Calculated from volume (5.9×10^4 km^3) of radar-detectable ash cloud and ash concentration shown in column 3.

[4]Calculated by Rose and Hoffman (1981).

[5]The ash-fall intensity (mm/hr) = (10 mm/cm) x (3.6×10^3 s/hr) x (concentration of ash in cloud, g/cm^3) x (terminal velocity of particles, cm/s) x (density of uncompacted air-fall ash, g/cm^3). A density of 1.0 g/cm^3 was assumed for the uncompacted air-fall ash.

represents our best estimate for the peak ash-fall rate sustained for a period of about 30 min. Also, we have estimated the minimum potential ash-fall areas and amounts (table 35). These data suggest, in retrospect, that for any reasonable duration of ash fall, the impact from the first ash cloud of the May 18 eruption ought to have been great.

The prospects for making useful ash-fall forecasts from radar and field observations appear good. However, such forecasting capability will require additional detailed radar observations of ash clouds, measurements of ash-fall intensities, studies of ash-fall mechanisms in eruption clouds, and comparison of radar observations with the actual distribution, times, and amounts of ash fall.

ONSET OF ASH FALL IN EASTERN WASHINGTON

Ash fall began at Tampico, Wash. (about 30 km west-southwest of Yakima), at about 1000 PDT. According to Seattle radar observations, the leading edge of the first ash cloud reached Yakima at about 0950 PDT and the trailing edge remained until after 1100. The same ash cloud, as tracked on the Spokane radar, reached Pullman, Wash., at about 1400 PDT (fig. 191), at which time ash fall began there (Hooper and others, 1980). Thus, ash fell for more than 4 hr from the first ash cloud as it moved from Tampico to Pullman.

Table 35.—Potential ash-fall amounts estimated from radar observations

[Data based on the following assumptions: potential ash-fall volume = 0.20 km³; potential ash-fall mass = 5.0×10^{14} g; ash cloud width = 70 km; horizontal speed of ash cloud = 135 km/hr; uncompacted density of air-fall ash = 1.0 g/cm³; complete dissipation of ash cloud, and constant ash-fall intensity. Results have been rounded]

Assumed duration of ash fall (hr)	Minimum potential ash-fall area (km²)	Estimated mean ash fall (mm)	(g/cm²)
1	10,000	50	5.0
2	20,000	25	2.5
5	50,000	10	1.0
10	100,000	5	0.5
20	200,000	2.5	0.25

According to photographs of eastern Washington on May 18, the ash cloud obscured the sky for periods of up to several hours prior to onset of ash fall at ground level. The duration of the obscured sky may be the time required for the fine-grained ash to fall to the ground from heights of 5–20 km in the atmosphere. It seems likely that the secondary maximum of ash-fallout thickness around Ritzville, Wash. (Sarna-Wojcicki and others, this volume), may be due to the rapid eastward transport of fine-grained (and slowly falling) ash from the first (and possibly later) eruptive pulses.

ESTIMATES OF MAGMA ERUPTION RATE

The maximum height to which Plinian eruption columns rise is a sensitive indicator of the magma eruption rate (Wilson and others, 1978). Measured column heights from the Portland radar and calculated magma eruption rates for the May 18 eruption are shown in table 33. They show that magma eruption rates during the early part of the eruption (about 0845–0900 PDT) were an order of magnitude higher than during most of the remainder of the 9-hr eruption. The total magma volume, which is suggested by these rates, can be estimated by considering the duration of the eruption. From the data in table 33, a total volume of about 0.15 km³ of dense dacite is suggested. This estimate assumes high efficiency of heat transfer to the atmospheric air entrained by the rising Plinian column, an efficiency which is not achieved in the case of pyroclastic flows. It also assumes that no interaction of ground water with magma occurred. Both of these assumptions are probably incorrect and will result in underestimation of the true magma volume. (See also Wilson and others, 1978.)

Such calculations illustrate that an "order of magnitude" volume estimate can be obtained from column-height measurements if the duration of the eruption is also known. Using radar data for later eruptions (for example, from table 36), we calculated dense-magma volumes of 0.002, 0.003, 0.003, 0.001, and 0.001 km³ for the eruptions of May 25, June 12, July 22, August 7, and October 16–18, 1980, respectively. These calculations illustrate the much smaller magnitudes of these later eruptions of Mount St. Helens, as compared to the May 18 eruption.

CONCLUSIONS

Radar observations show that the Plinian eruption of Mount St. Helens on May 18 lasted for about 9 hr. The maximum height of the Plinian eruption column (> 24 km above sea level) was attained several minutes after the eruption began (0832 PDT); however, by 0900 PDT the column height immediately over the vent was only about 16 km and continued to decrease. After 0900 PDT, the height of the eruption column exceeded 14 km for an additional 8½ hr. During the 9-hr eruption there were four periods of relatively increased height and reflectivity of the Plinian column, which probably resulted from increased rates of ash emission. Radar observations of discrete ash clouds downwind from the volcano also suggest that the eruption had four distinct relative maxima in the rate of ash emission.

Table 36.—Maximum heights of Plinian eruption columns at Mount St. Helens

Date (1980)	Maximum column heights of successive pulses (km)	Duration of ash emission with column height >12 km (relative to sea level)
May 18	>24, 17.3, 14.6, 19.2	About 9 hr.
May 25	12.2	<30 min.
June 12	15.2, 10.7, 9.8, 10.7	About 30 min.
July 22	13.7, 14.5, 8.7	25 min.
Aug. 7	13.4, 10.0, 6.1, 7.6, 6.1, 5.2.	2 to 5 min.
Oct. 16	12.8	<5 min.
Oct. 17	14.3, 13.7	Do.
Oct. 18	5.2, 7.9, 6.1	0 s.

A mean particle concentration of 8.5 g/m^3 is inferred for the first ash cloud downwind from Mount St. Helens, about 1.5–2 hr after the 0832–0900 Plinian eruption. The mass of silicate particles in the cloud (5×10^{14} g) was estimated using the total ash-cloud volume (5.9×10^4 km^3) and the particle concentration. The potential ash-fall volume calculated for the radar-detected portion of the ash cloud is 0.20 km^3.

Radar observations of Plinian eruptions at Mount St. Helens subsequent to the May 18 eruption show that the later ones were of shorter duration and erupted much smaller volumes of ash as compared to the May 18 eruption.

REFERENCES CITED

Atlas, D., 1964, Advances in radar meteorology, *in* Landsberg, H. E., and Van Mieghem, J., eds., Advances in geophysics, volume 10: New York, Academic Press, p. 317–479.

Atlas, D., and Chmela, A. C., 1957, Physical-synoptic variations of drop-size parameters: American Meteorological Society Weather Radar Conference, 6th, Boston, Proceedings, v. 4, p. 21–29.

Blanchard, D. C., 1953, Raindrop size distribution in Hawaiian rains: Journal of Meteorology, v. 10, p. 457–473.

Campbell, M. J., and Ulrichs, J., 1969, Electrical properties of rocks and their significance for lunar radar observations: Journal of Geophysical Research, v. 74, p. 5867–5881.

Hooper, P. R., Herrick, I. W., Laskowski, E. R., and Knowles, C. R., 1980, Composition of the Mount St. Helens ashfall in the Moscow—Pullman area on 18 May 1980: Science, v. 209, p. 1125–1126.

Johnston, D. A., 1978, Volatiles, magma mixing, and the mechanism of eruption of Augustine volcano, Alaska: University of Washington, Seattle, Ph. D. thesis, 177 p.

Jones, D. M. A., 1956, Rainfall drop-size distribution and radar reflectivity: Illinois State Water Survey, Meteorology Laboratory Research Report no. 6, 20 p.

Probert-Jones, J. R., 1962, The radar equation in meteorology: Quarterly Journal of the Royal Meteorological Society, v. 88, p. 485–495.

Rose, W. I., Jr., 1977, Scavenging of volcanic aerosols by ash—atmospheric and volcanologic implications: Geology, v. 5, p. 621–624.

Rose, W. I., Jr., Chuan, R. L., Cadle, R. D., and Woods, D. C., 1980, Small particles in volcanic eruption clouds: American Journal of Science, v. 280, p. 671–696.

Rose, W. I., Jr., and Hoffman, M. F., 1980, Distal ashes of the May 18, 1980, eruption of Mount St. Helens [abs.]: Transactions of the American Geophysical Union, v. 61, p. 1137.

______1981, The May 18 eruption of Mount St. Helens—the nature of the eruption, with an atmospheric perspective, *in* Deepak, A., ed., NASA Symposium on the Mount St. Helens eruption—Its atmospheric effects and potential climatic impact: Hampton, Va., Institute for Atmospheric Optics and Remote Sensing (IFAORS).

Wexler, R., and Atlas, D., 1963, Radar reflectivity and attenuation of rain: Journal of Applied Meteorology, v. 2, p. 276–280.

Wilson, L., Sparks, R. S. J., Huang, T. C., and Watkins, N. D., 1978, The control of volcanic column heights by eruption energetics and dynamics: Journal of Geophysical Research, v. 83, p. 1829–1836.