Rapid eruption detection and volcanic ash cloud characterization using weather radar: Current capabilities and limitations

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Summary

- Weather radars can provide:
  - Near-real time observation and height determination of volcanic eruptions.
  - Mass and particle size retrievals are possible
  - Discrimination of ash and hydrometeors with polarized radar. (Frank Marzano)
- Demonstrated use by groups in Iceland, Italy, Japan and the United States (others?).
- Sensitivity to large particles is a limitation.
- Typically operated by meteorological agencies and in some cases not available VAACS and volcano observatories.

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Recommendations

- Encourage collaboration and access to radar data.
- Development of derived volcanic ash products and scanning strategies for meteorological agencies.
- Construct an inventory of available meteorological radars that are located near volcanoes.

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Why use radar???

- **Existing monitoring methods cannot, by themselves, <u>unambiguously</u> detect explosive eruptions when the volcano is not visible.** **Volcanoes commonly can't be observed directly due to inclement weather, darkness, persistent clouds, or remote location.**
- **The simultaneous occurrence of a seismic event and the appearance of a cloud over the volcano provide incontrovertible evidence that an explosive event has occurred and that ash is in the air.**

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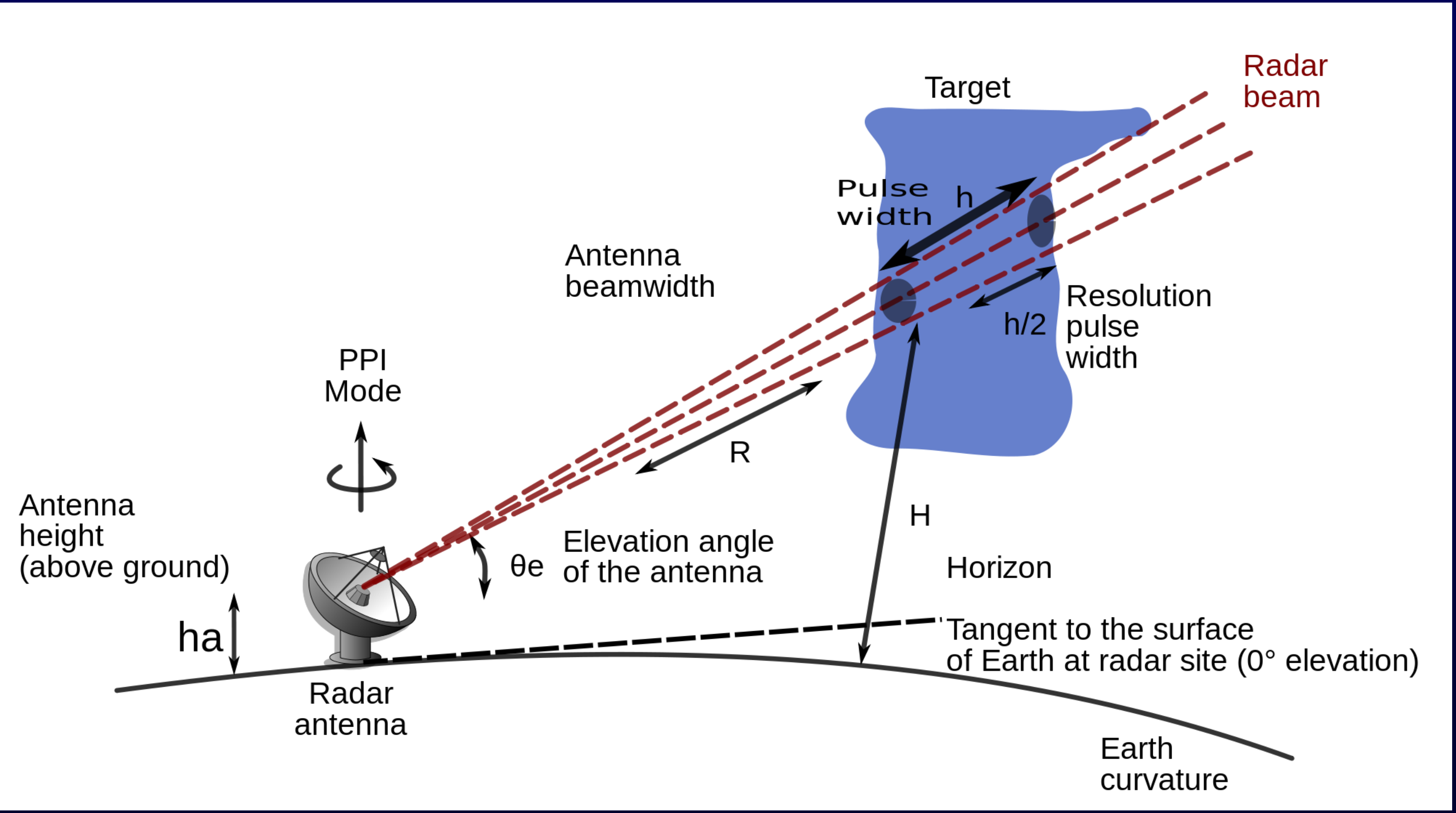
Ash hazard mitigation

- Eruption onset forecast and detection
- Confirmation of ash emission
- Modeling of ash dispersion and fallout
  - Altitude and movement of ash cloud
  - Vertical mass distribution
  - Eruption duration
  - Ash removal processes
- Radar can provide near-real time data that compliments seismic monitoring and satellite observations.


Target
Radar
beam
Pulse
width
h
Antenna
beamwidth
Resolution
pulse
width
h/2
PPI
Mode
R
Antenna
height
(above ground)
H
Elevation angle
of the antenna
θe
Horizon
ha
Tangent to the surface
of Earth at radar site (0° elevation)
Radar
antenna
Earth
curvature

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USGS Volcano Radar Experience

- Mount St. Helens, Washington, 1980
  - (WSR-74C: NWS and FAA: Seattle, Spokane)
- Pinatubo, Philippines, 1991
  - (AN/FPS-77: Clark AFB and AN/FPS-106: Cubi Point NAS).
- Mount Spurr, Alaska, 1992
  - (WR 100-2 C: NWS lease)
- Popocatepetl, Mexico 1997-1999
  - (Kavouras Triton C-band: USGS)
- Augustine, Alaska, 2006
  - (WSR-88D: FAA)
- Fourpeaked, Alaska, 2006
  - (WSR-88D: FAA)
- Redoubt, Alaska, 2009
  - (EEC Minimax C-band: USGS and WSR-88D: FAA)

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Doppler Radar Moments

- Reflectivity: Backscatter from particles within the scan volume. Amplitude depends upon the particle size, concentration and dielectric factor.

- Radial Velocity: Movement of particles within a scan volume, determined by phase shift between consecutive pulses.

- Spectrum Width: Measure of the velocity variance (due to turbulence) within a scan volume.

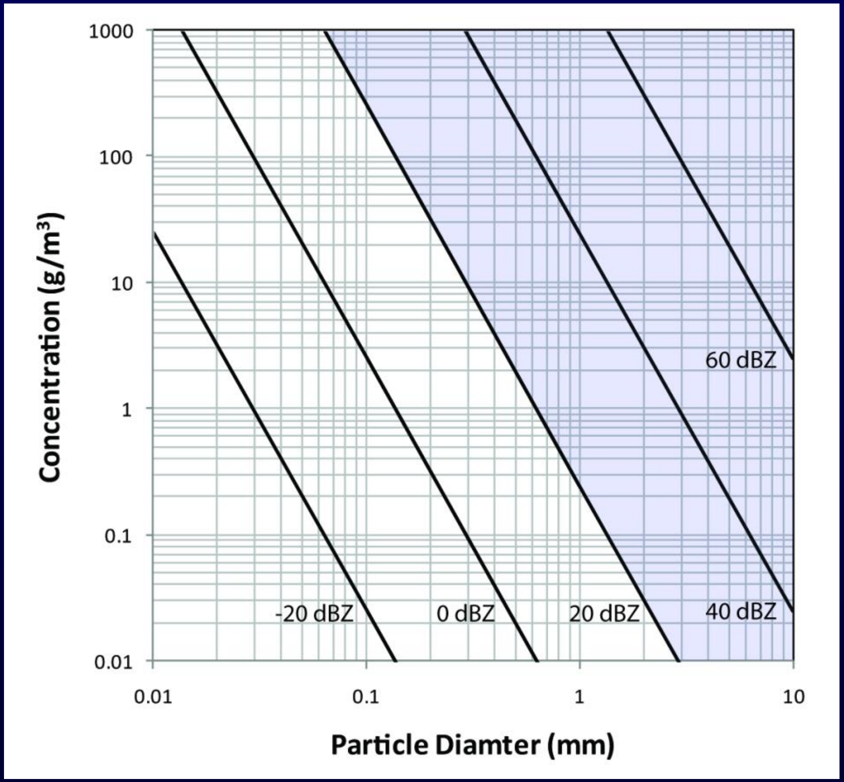
Radar reflectivity, particle size and mass concentration

- Idealized plot for spherical ash particles, all of the same size.
- Radar reflectivity factor

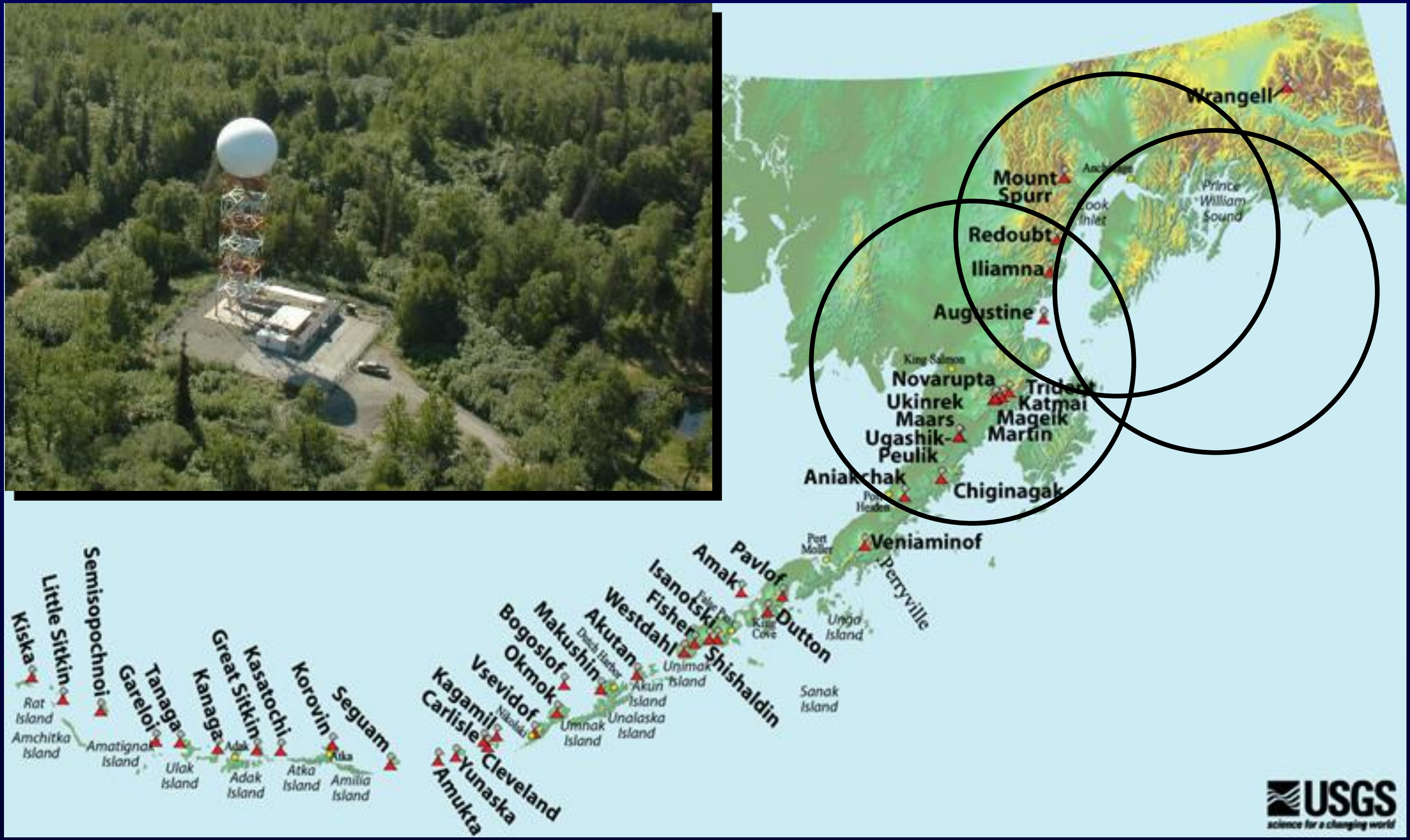
$$z = \sum N_i D_i^6$$

where N_i is the number of particles of diameter D_i per unit volume

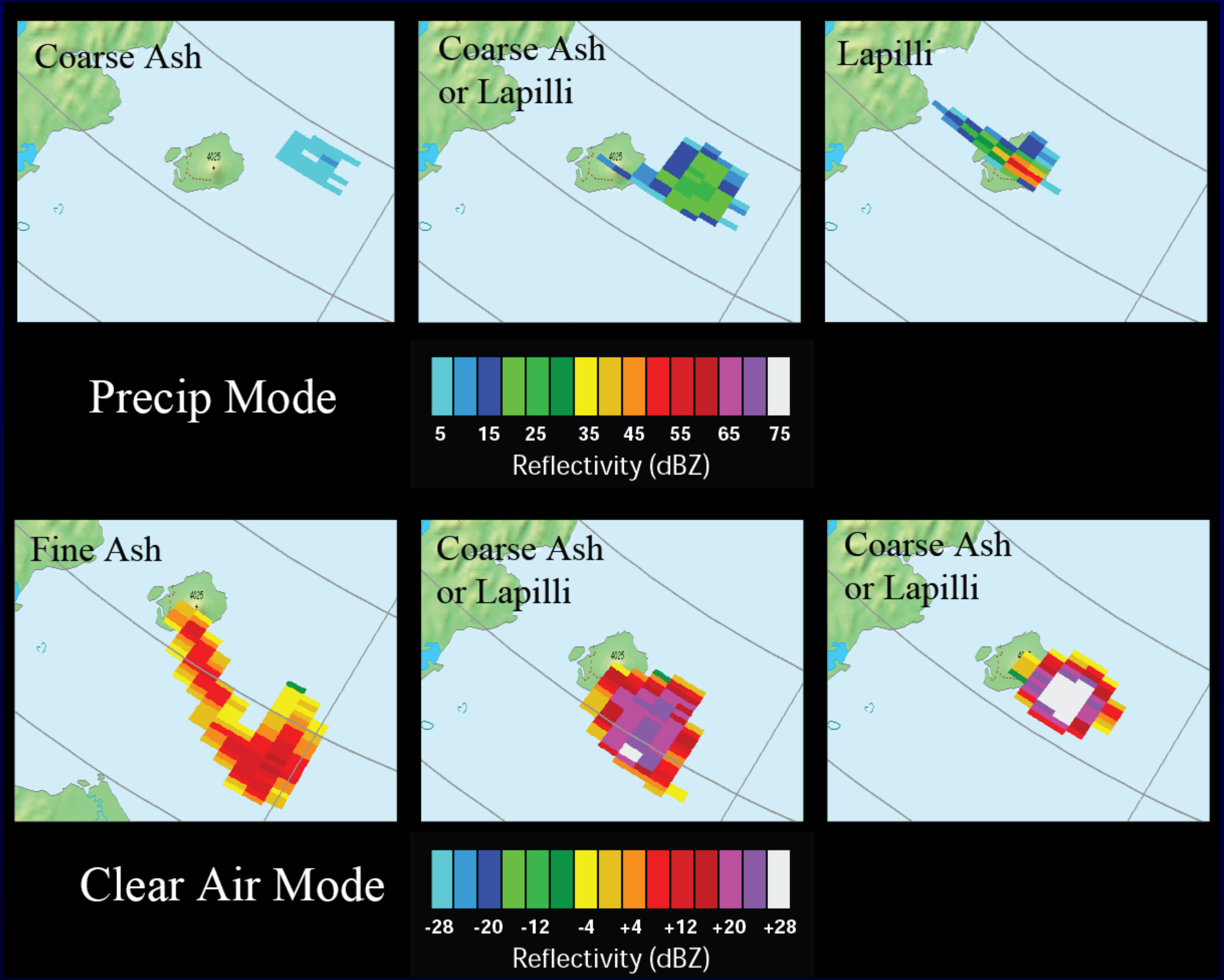
- Thus reflectivity dominated by large particles. Typically expressed as logarithmic reflectivity factor (dBZ).



Alaska NEXRAD and Volcanoes:
250 km Range



Augustine NEXRAD 2006



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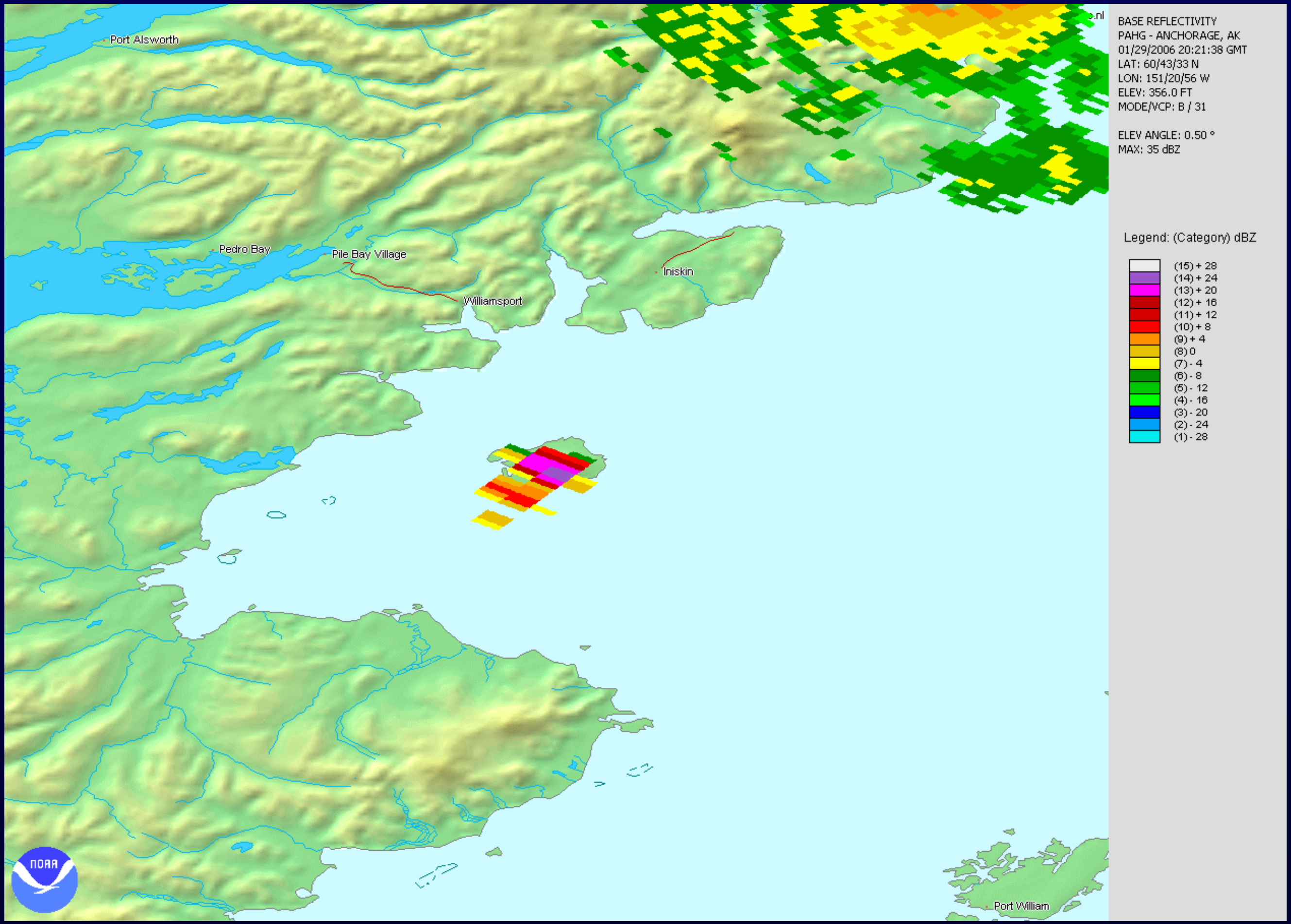
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Pile Bay Village
Williamsport
Iniskin
Port William
NOAA
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MODE/VCP: B / 31
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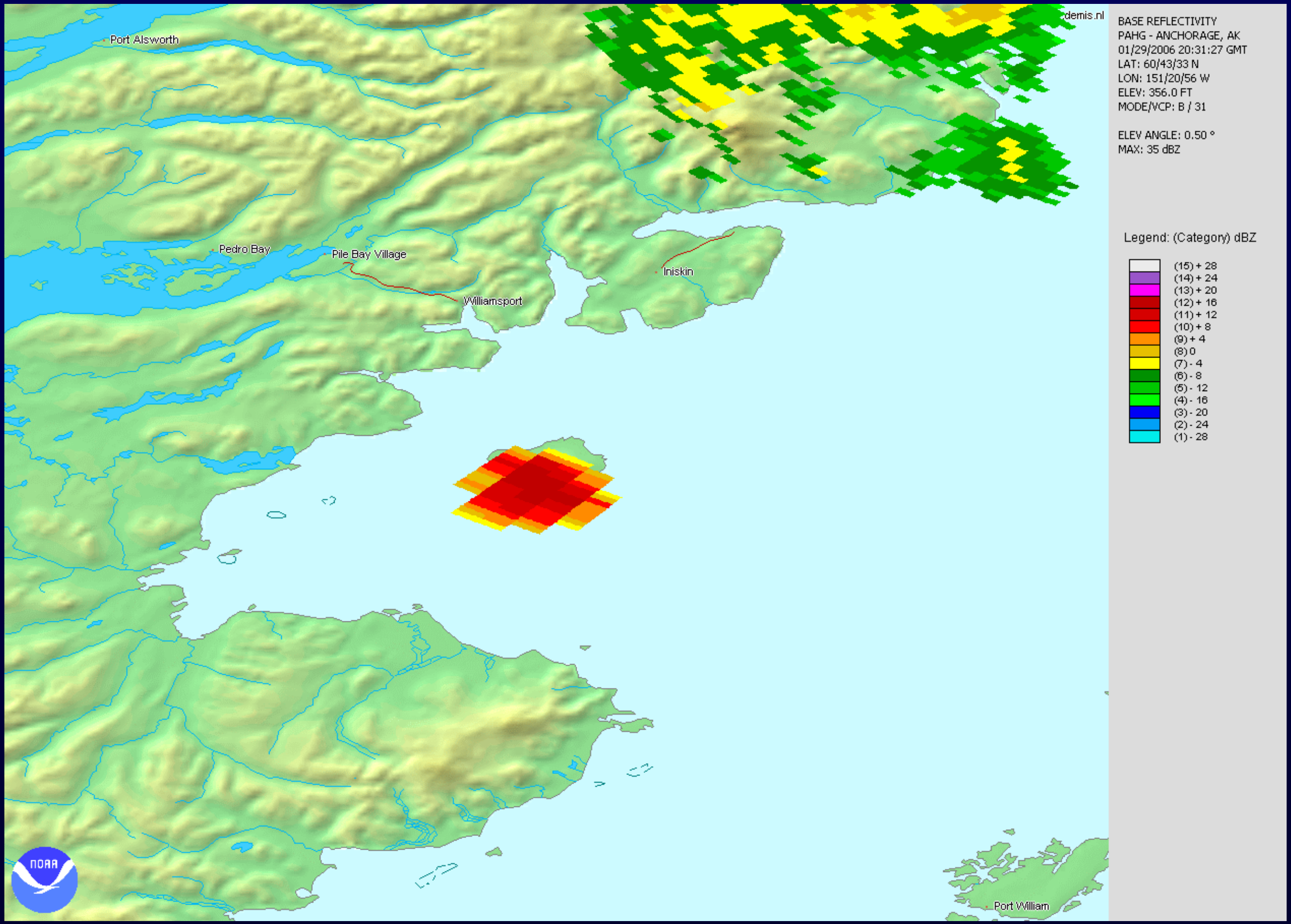
MAX: 35 dBZ
Legend: (Category) dBZ
(15) + 28
(14) + 24
(13) + 20
(12) + 16
(11) + 12
(10) + 8
(9) + 4
(8) 0
(7) - 4
(6) - 8
(5) - 12
(4) - 16
(3) - 20
(2) - 24
(1) - 28

USGS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(11) + 12
(10) + 8
(9) + 4
(8) 0
(7) - 4
(6) - 8
(5) - 12
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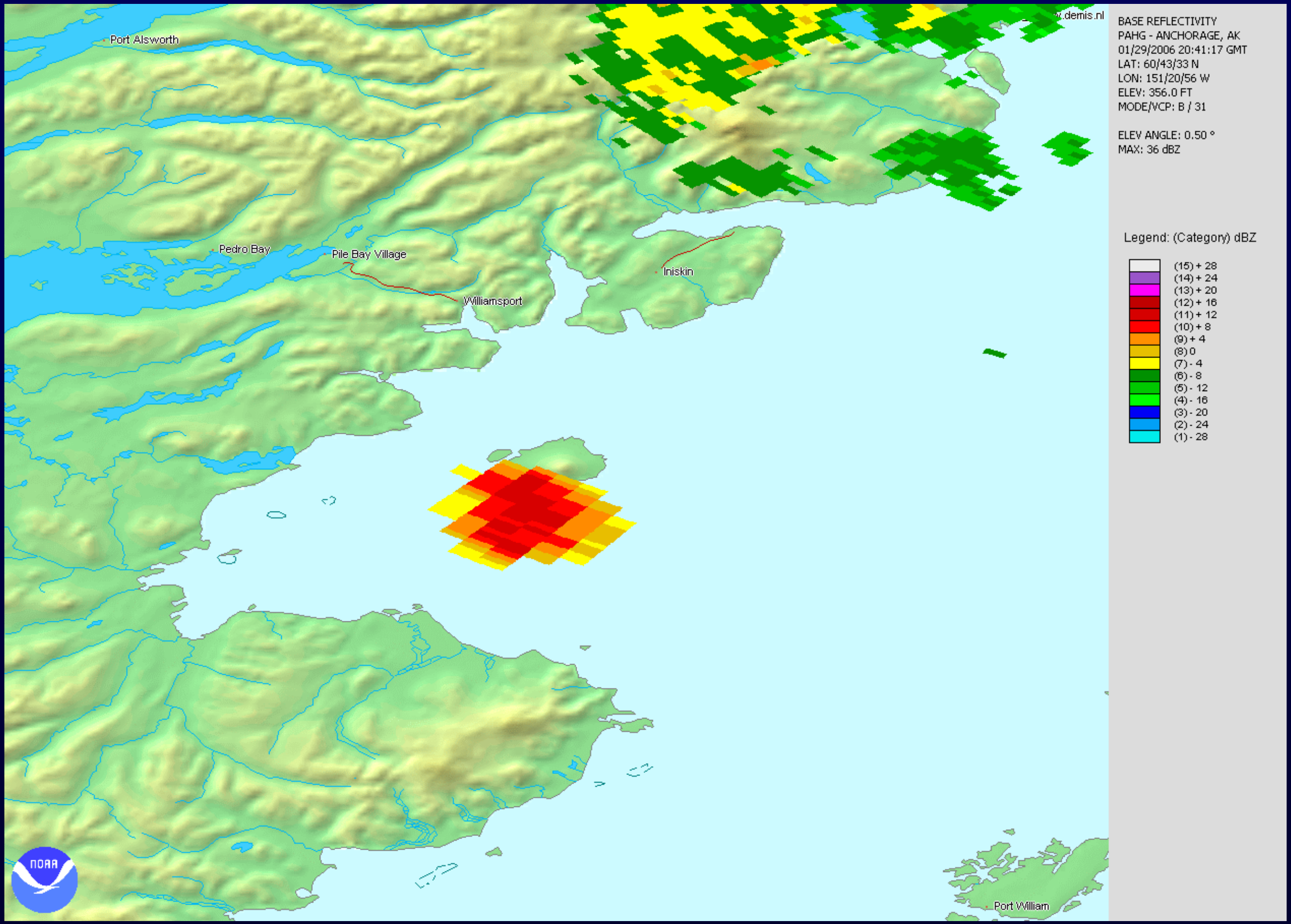
Pile Bay Village
Williamsport
Iniskin
Port William
NOAA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(1) - 28

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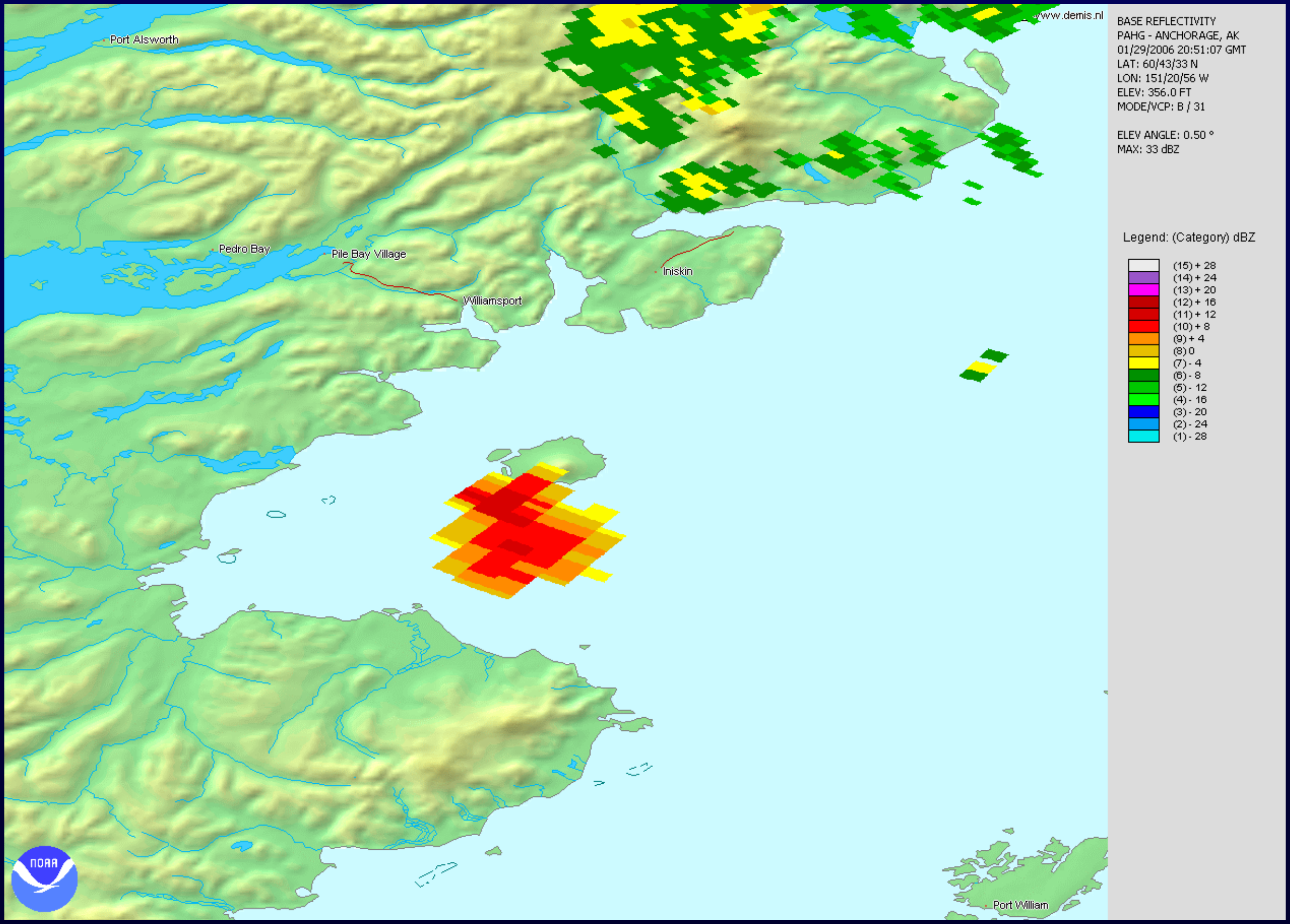
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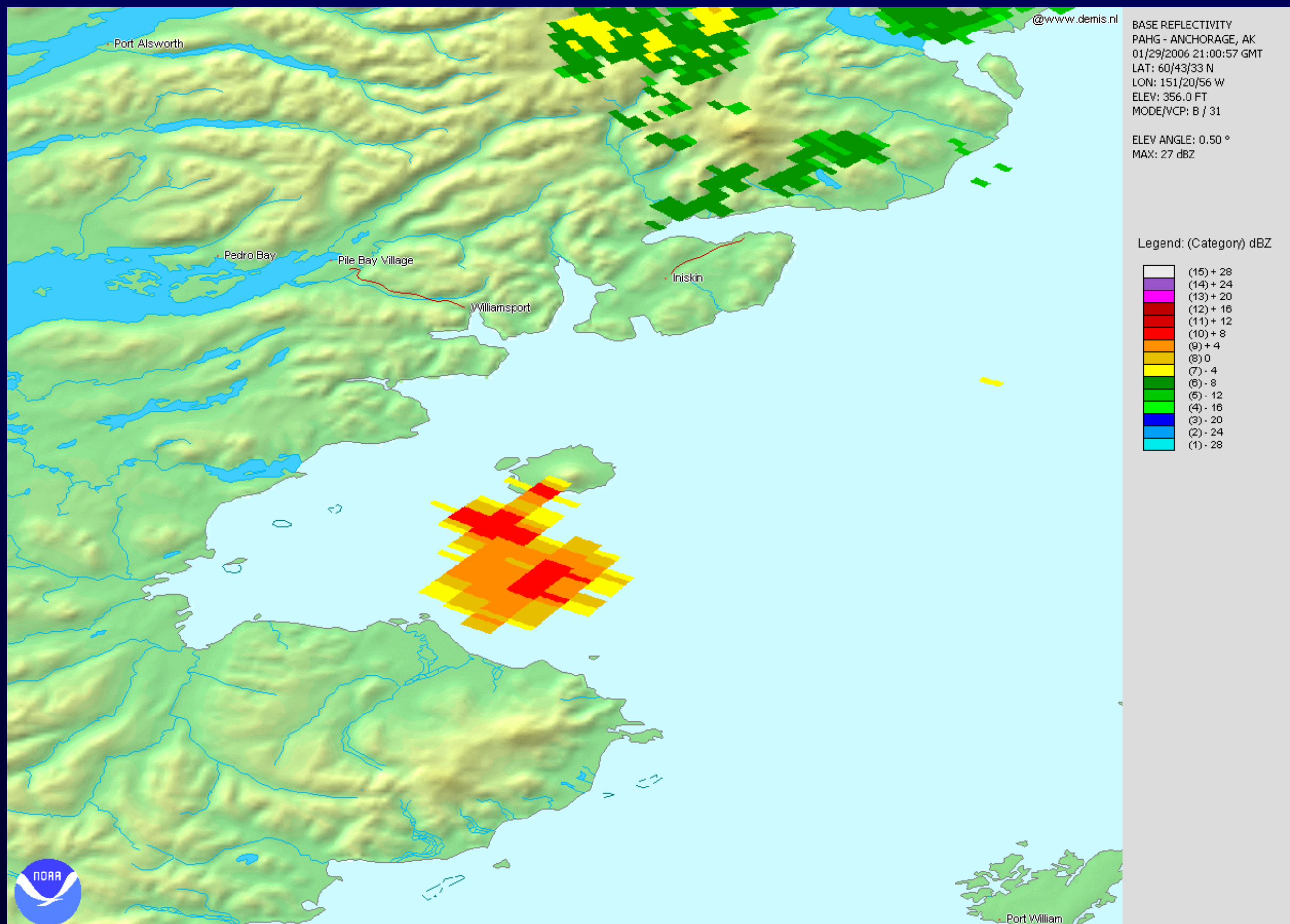

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(9) + 4
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(6) - 8
(5) - 12
(4) - 16
(3) - 20
(2) - 24
(1) - 28

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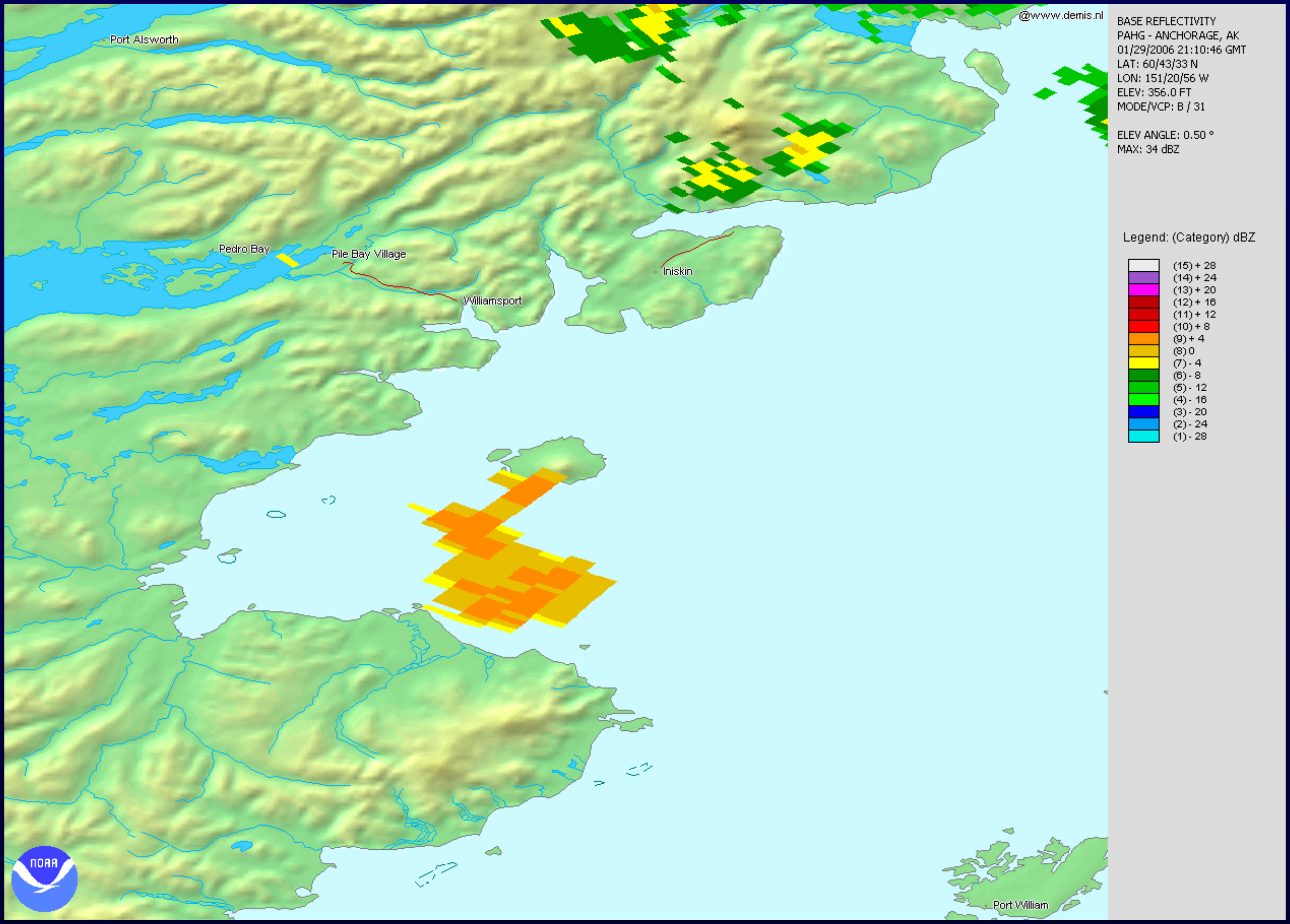
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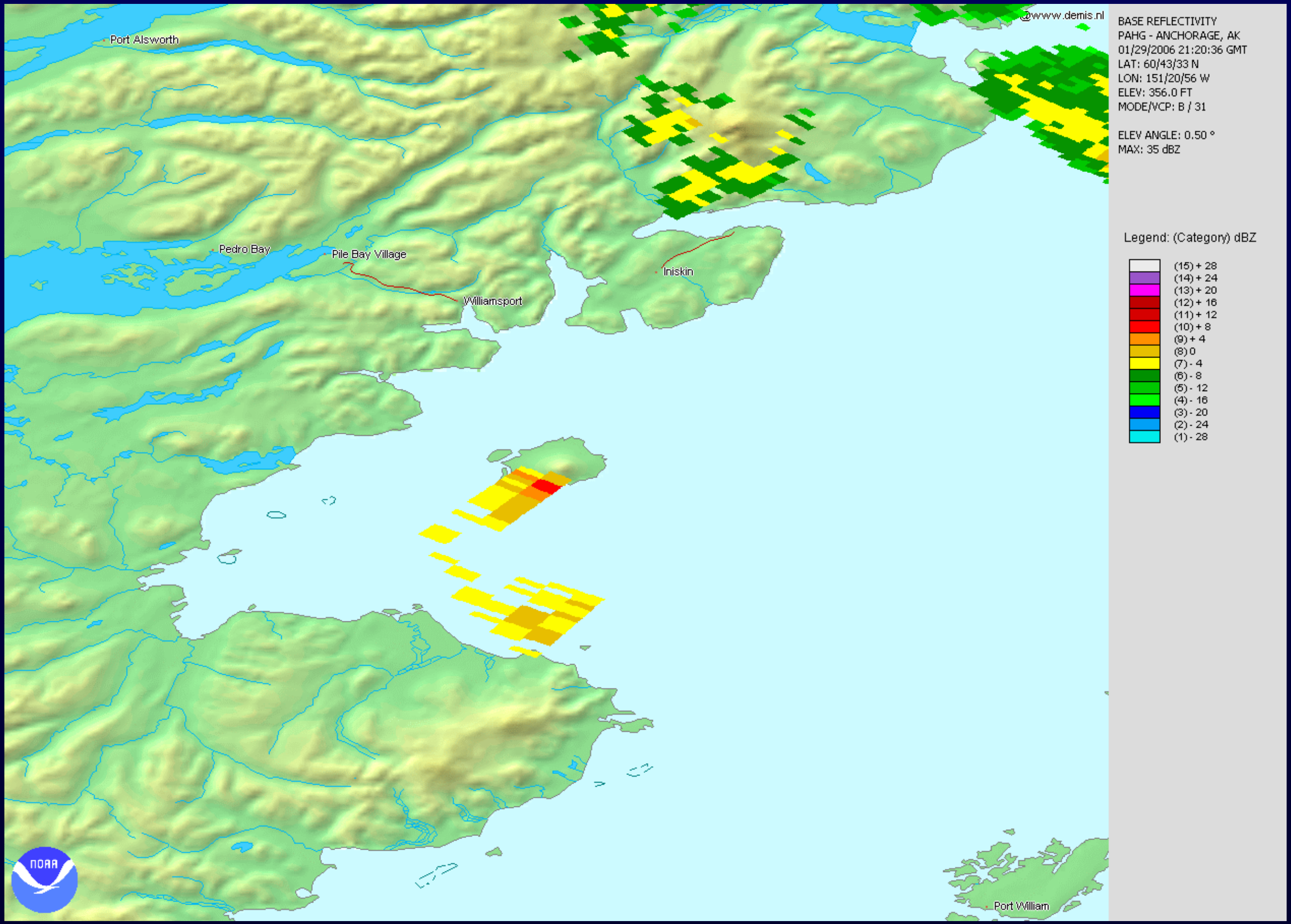
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LON: 151/20/56 W
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ELEV ANGLE: 0.50 °
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(11) + 12
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(9) + 4
(8) 0
(7) - 4
(6) - 8
(5) - 12
(4) - 16
(3) - 20
(2) - 24
(1) - 28

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Augustine Island Sun Jan 29 10:12:29 2006 Ex: 1000

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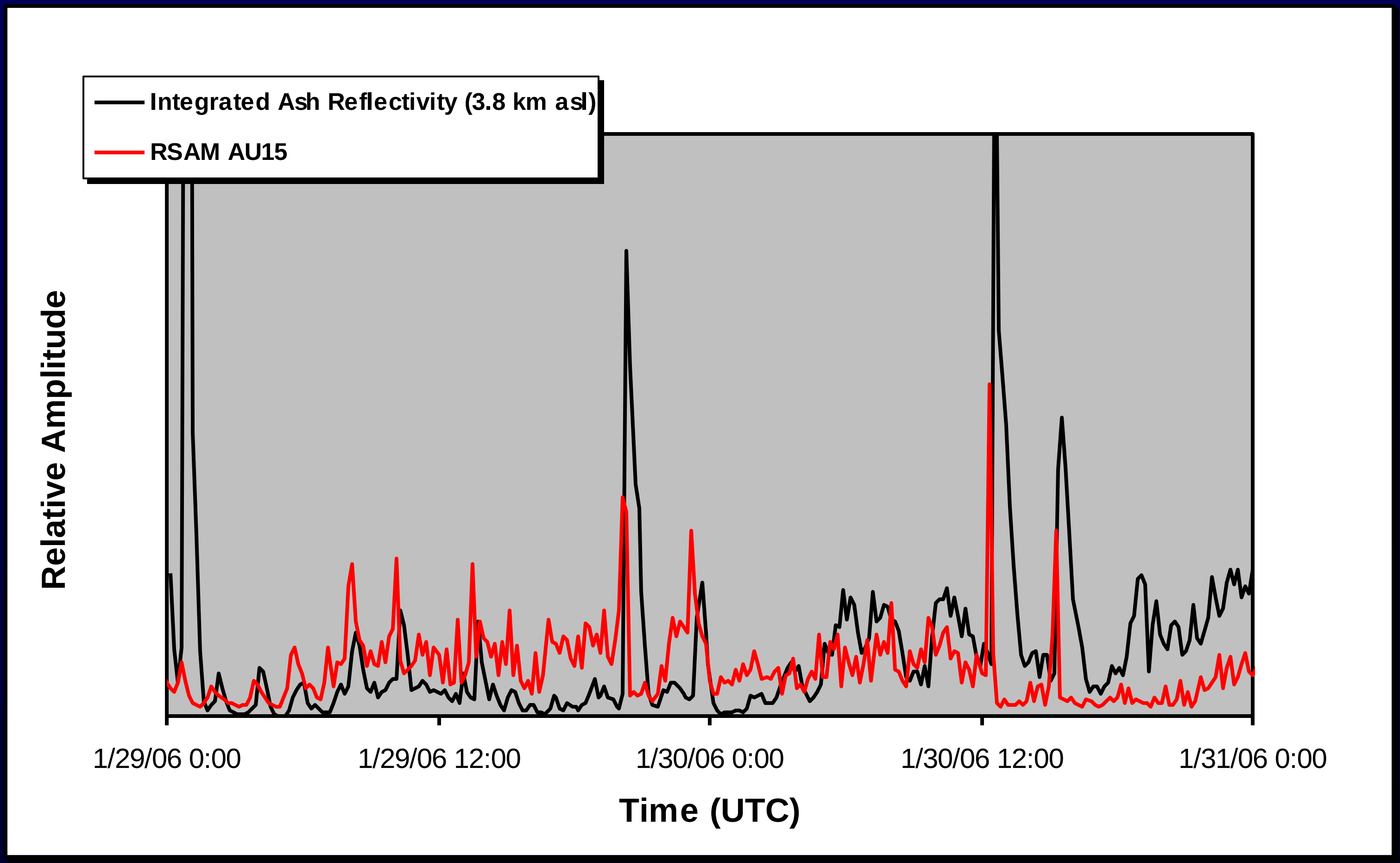
Integrated Ash Reflectivity (3.8 km asl)
RSAM AU15
Relative Amplitude
1/29/06 0:00
1/29/06 12:00
1/30/06 0:00
1/30/06 12:00
1/31/06 0:00
Time (UTC)

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USGS MM-250C Doppler Radar

- Dedicated volcanic ash radar deployed to observe Redoubt.
- Operational and controlled from Anchorage about 24 hours prior to first explosive event.
- Provided unprecedented observations of explosive eruption clouds.

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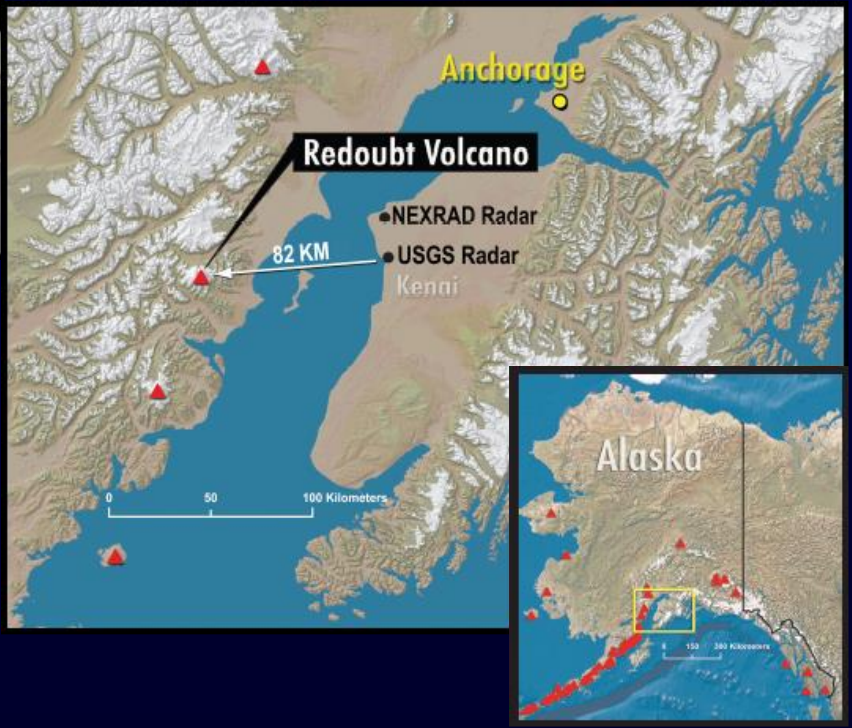
Location and view from site



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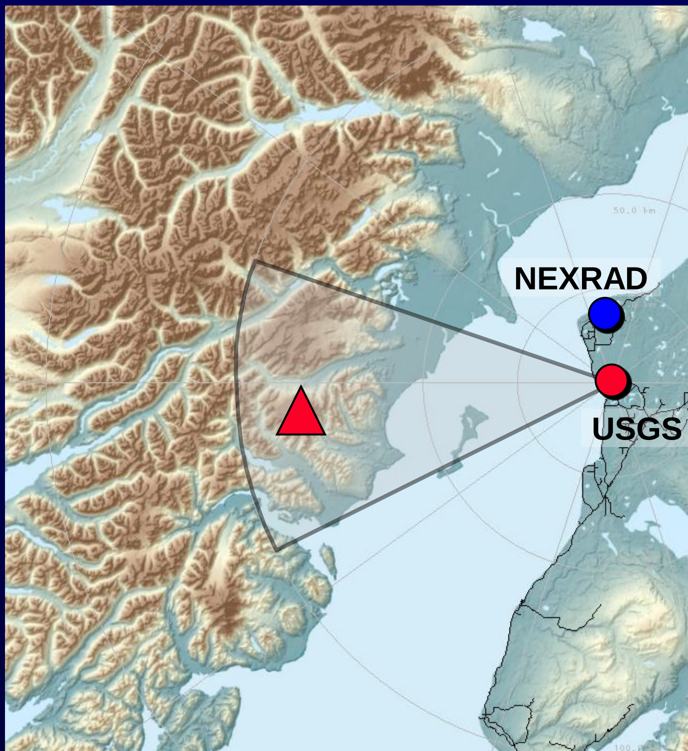
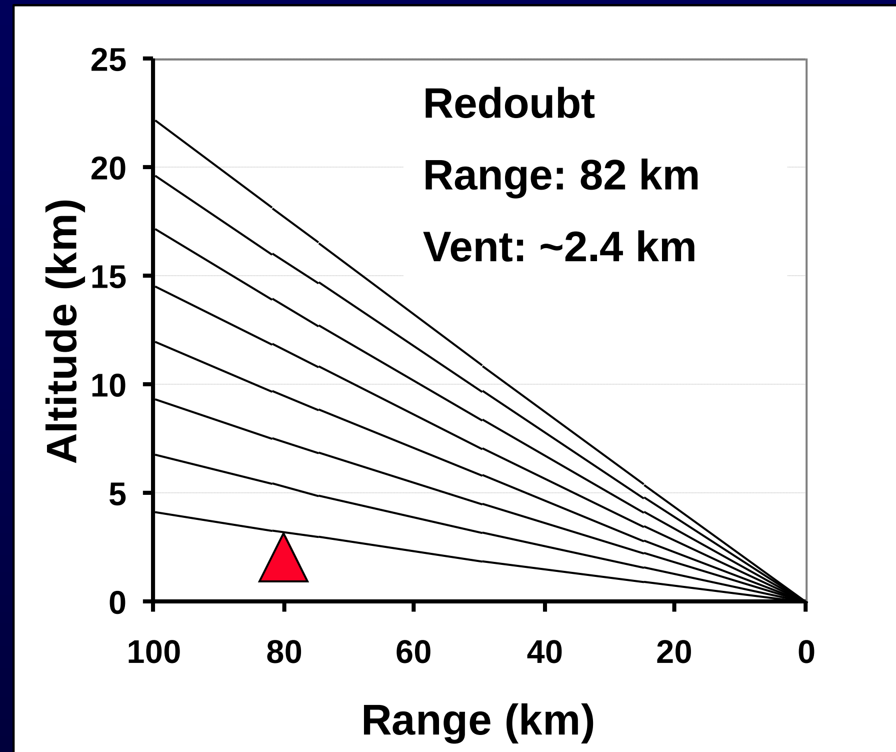
Typical scan strategy



45 Degree Sector Scan



8 Elevation Angles (Δ1.5º) in 90 s

Transmit Power: 250 W

Range: 100 km

Range Gate: 250 m

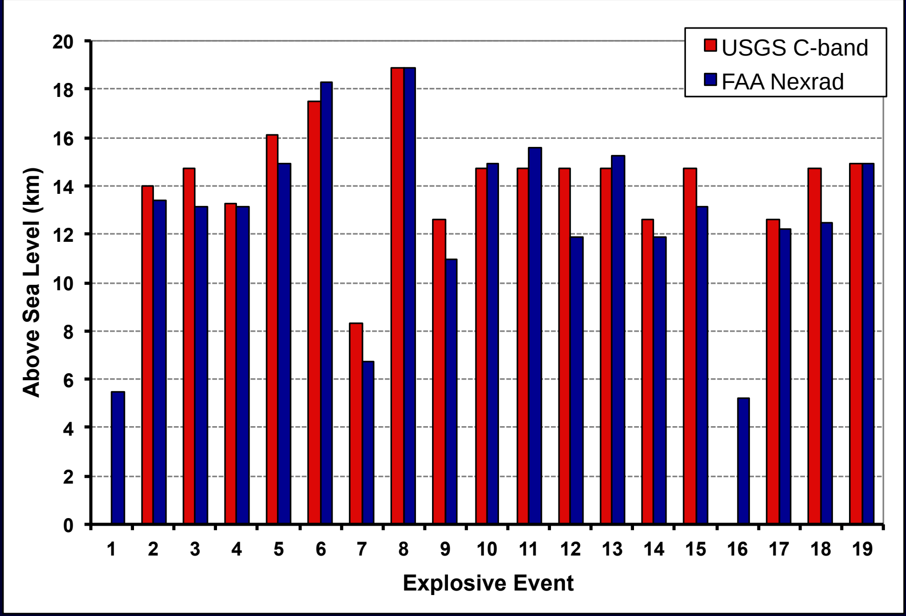
Pulse Length: 1.6 μs

PRF: 1000 Hz

Temporal resolution 3-6x better than NEXRAD

2009 Redoubt Eruption

- **Nineteen discrete explosive events between March 23 and April 4.**
- **Short eruption duration (minutes to tens of minutes).**
- **Eruption columns observed by USGS MM-250C and NEXRAD radars. Sixteen clouds into the stratosphere.**



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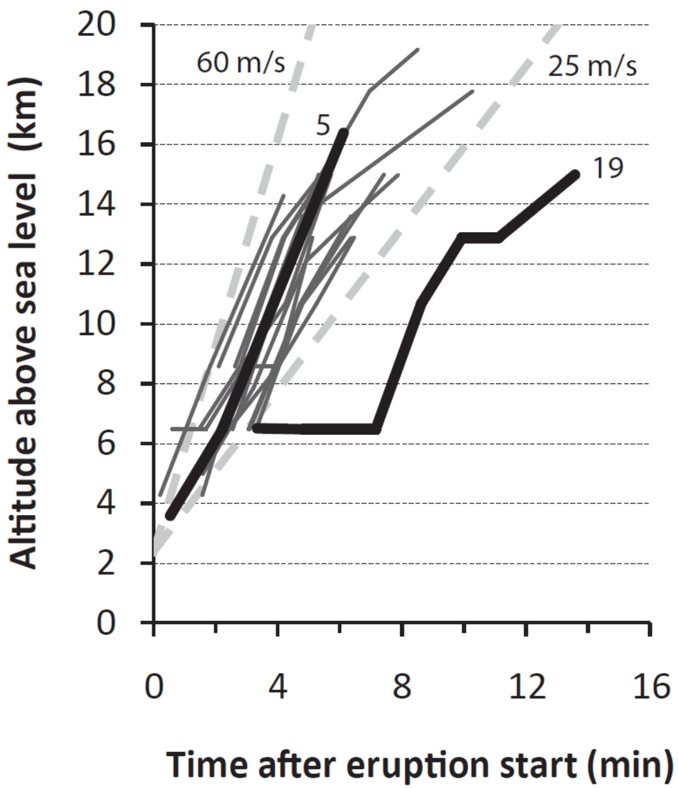
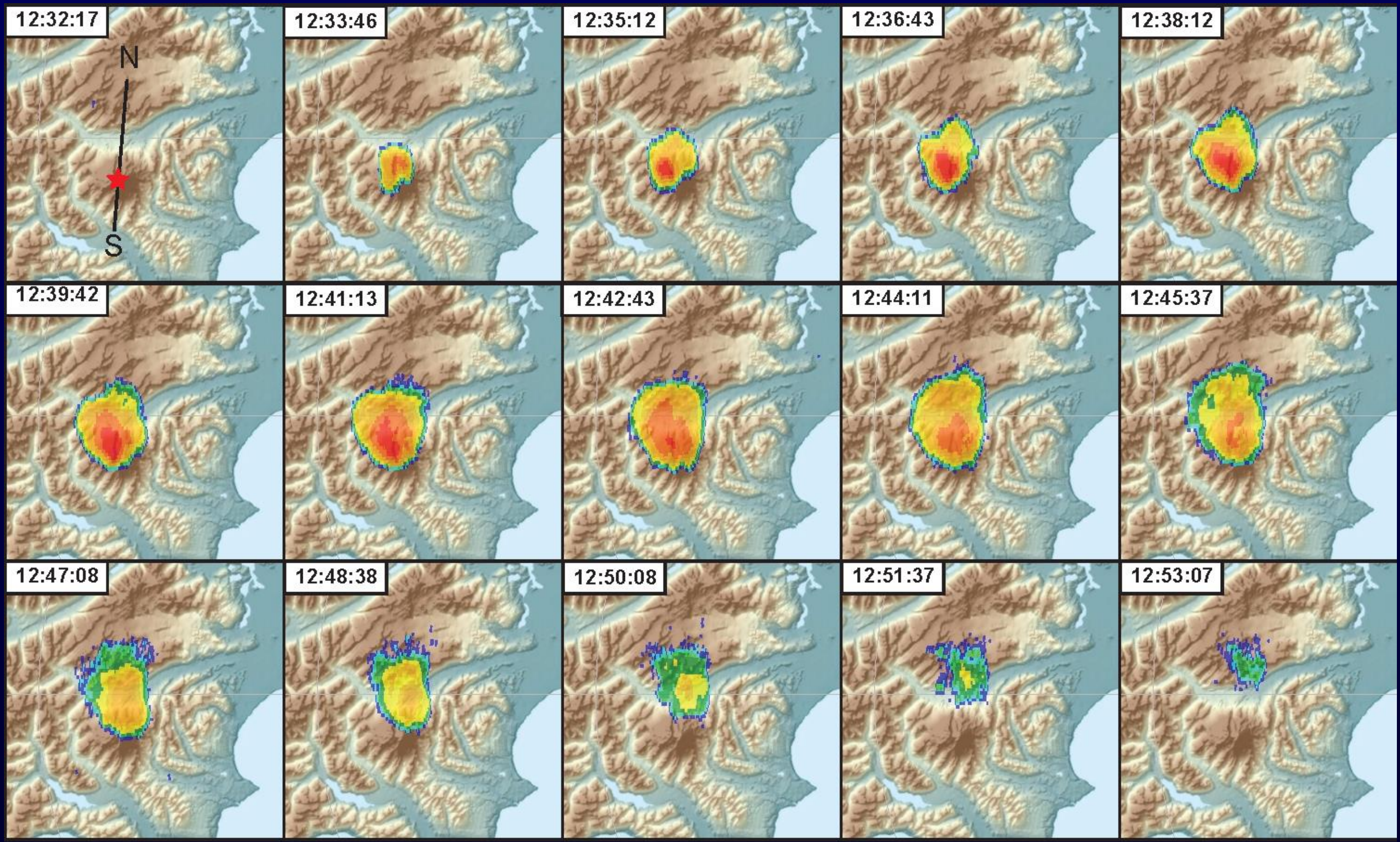
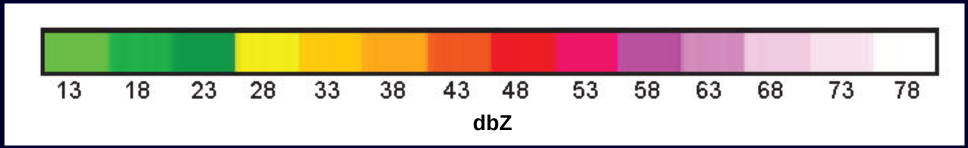


Altitude above sea level (km)
20
18
16
14
12
10
8
6
4
2
0
60 m/s
25 m/s
5
19
0
4
8
12
16
Time after eruption start (min)

“Event 5” reflectivity image
7.9 km asl





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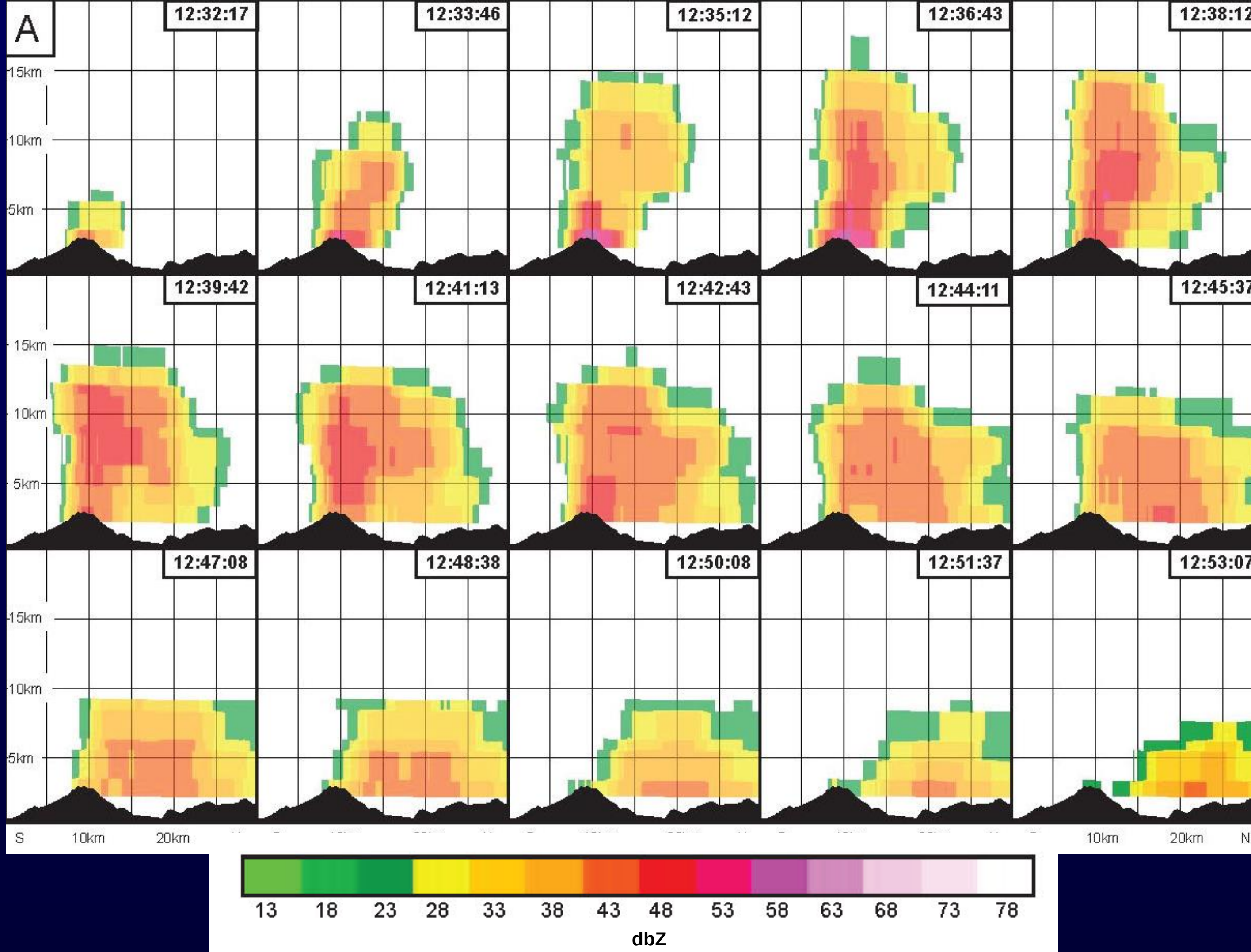
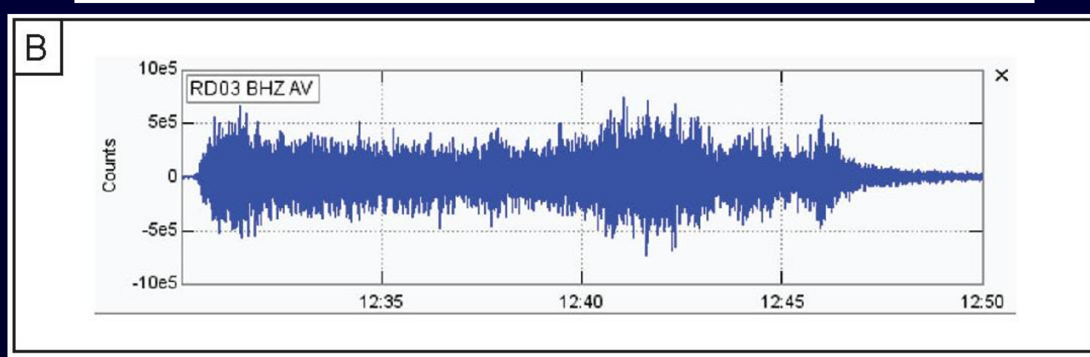

A
12:32:17
12:33:46
12:35:12
12:36:43
12:38:12
12:39:42
12:41:13
12:42:43
12:44:11
12:45:37
12:47:08
12:48:38
12:50:08
12:51:37
12:53:07
15km
10km
5km
S
10km
20km
N
13 18 23 28 33 38 43 48 53 58 63 68 73 78
dbZ


B
RD03 BHZ AV
10e5
5e5
0
-5e5
-10e5
Counts
12:35
12:40
12:45
12:50

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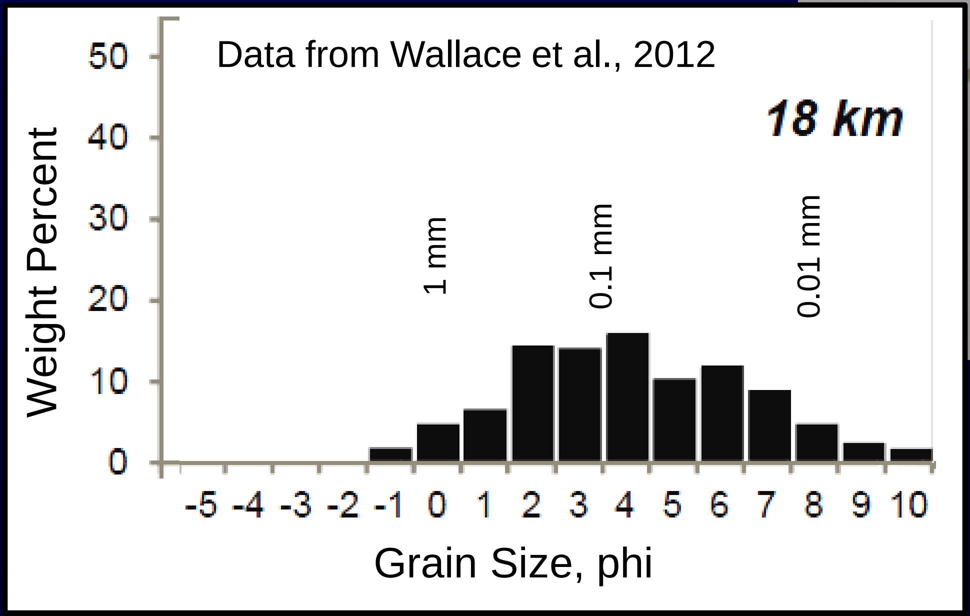
Rapid decrease in cloud height and reflectivity: Proximal fallout mm-sized aggregate pellets

Particle size distribution of melted aggregates



Frozen aggregates comprised of fine to very-fine grained ash

nature COMMUNICATIONS

ARTICLE

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OPEN

Hail formation triggers rapid ash aggregation in volcanic plumes

Alexa R. Van Eaton[1,2], Larry G. Mastin[1], Michael Herzog[3], Hans F. Schwaiger[4], David J. Schneider[4], Kristi L. Wallace[4] & Amanda B. Clarke[2]

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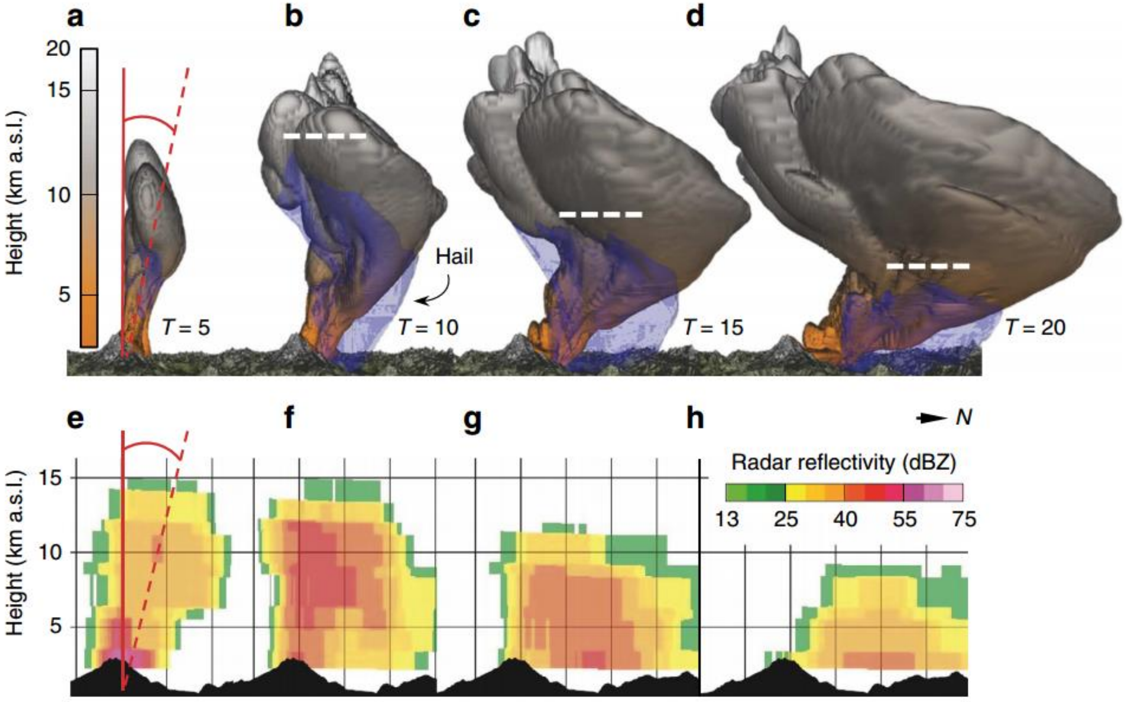

Figure 2 | Comparison of 3D large-eddy simulation and measured radar reflectivity. (**a–d**) Modelled plume at $T = 5$, 10, 15 and 20 min after eruption start. Note: eruption ends at $T = 6$ min. Total volcanic particles (sum of single-particle and aggregate size bins) shown as an isosurface coloured by height and hail as a transparent blue isosurface, both at 1 mg m^{-3} concentration. Dashed white lines show maximum height of hail isosurface. Fallout of hail in the model corresponds to the rapid descent of radar echo tops from ref. 20, which is shown in **e–h** as north–south cross-sections at roughly equivalent time steps. Distance between vertical lines is 5 km.

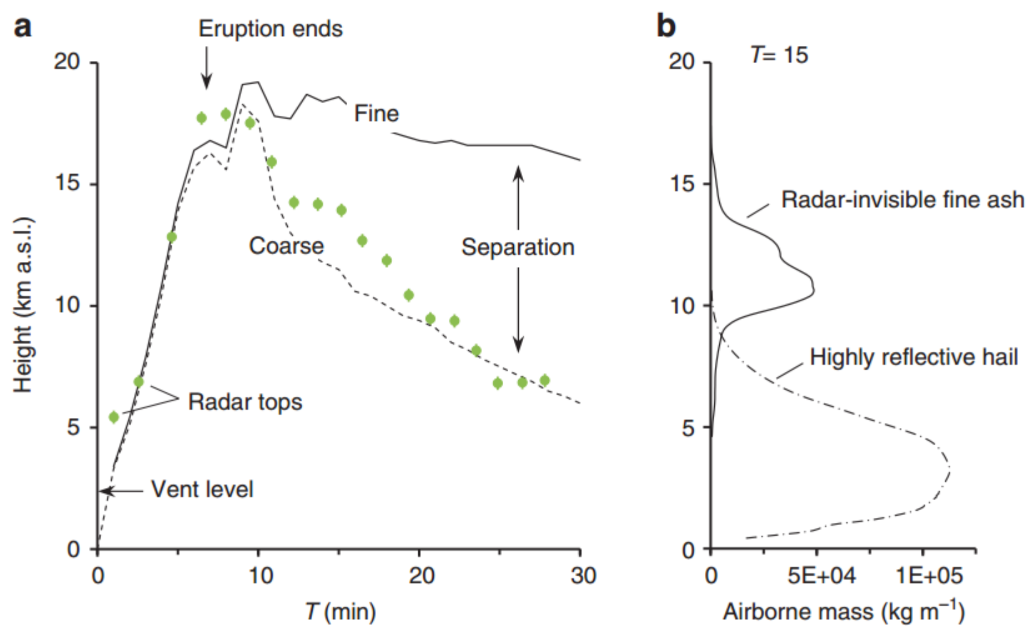

Figure 3 | Gravitational separation of particles in the event 5 volcanic plume from Redoubt Volcano. (**a**) Time series showing maximum heights of the radar-detected plume (green circles) and modelled particles (lines). Mean radar heights derived from the highest-angle scan containing the cloud in plan view; error bars give maxima and minima. Solid line shows fine particles ($\leq$250 μm); dashed shows coarse particles ($\geq$500 μm), both at concentrations $\geq$10 mg m^{-3}. (**b**) Modelled vertical distribution of mass at $T = 15$ min, showing horizontally integrated mass of fine ash (solid) and hail (dot-dash).

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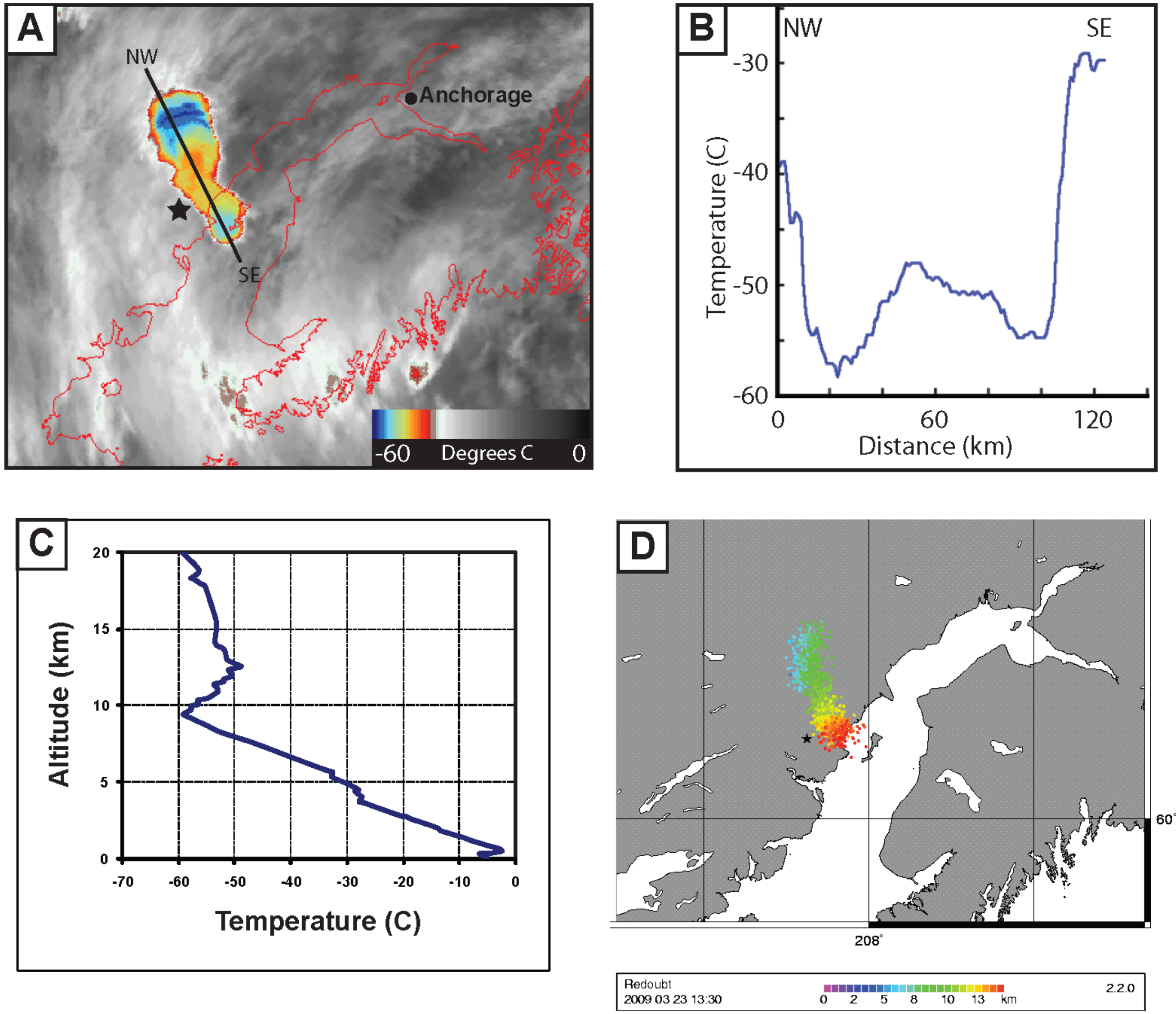
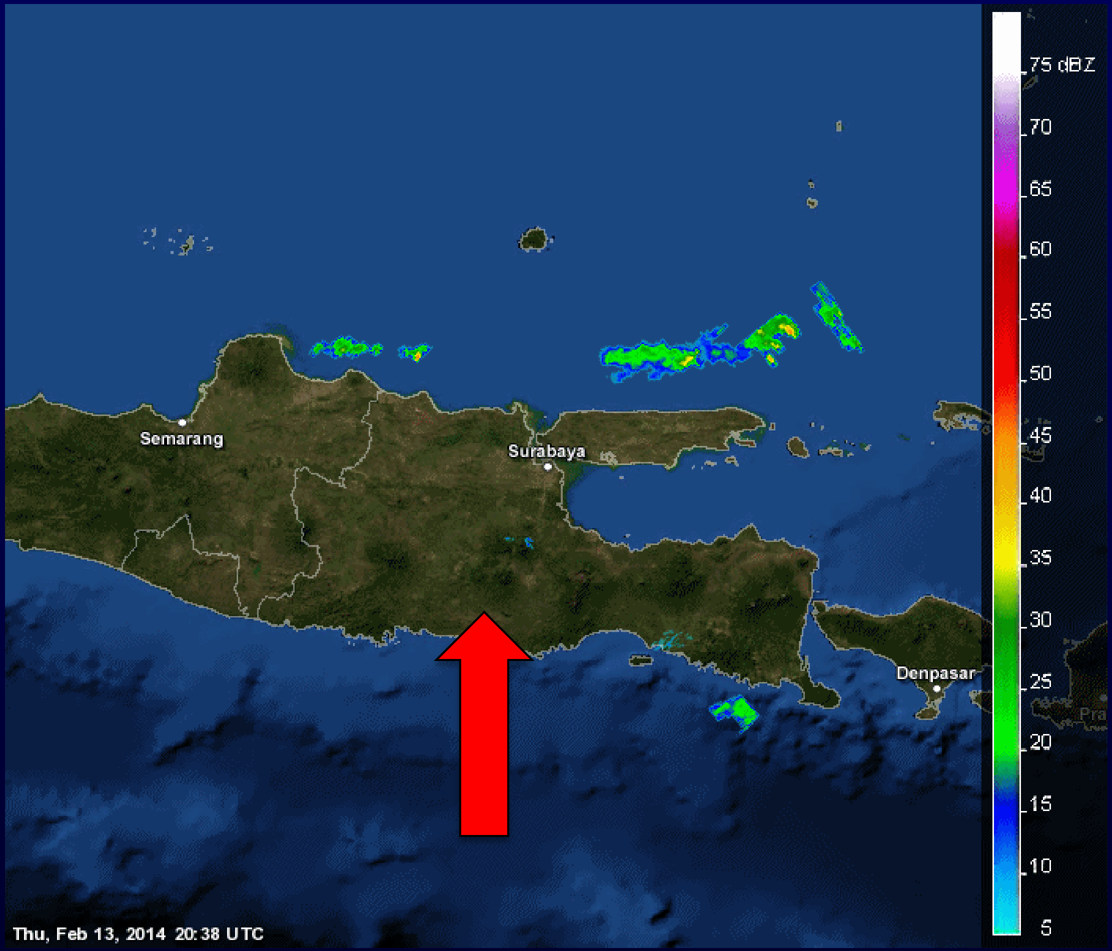

A
NW
SE
Anchorage
-60
Degrees C
0
B
NW
SE
Temperature (C)
-30
-40
-50
-60
0
60
120
Distance (km)
C
Altitude (km)
20
15
10
5
0
-70
-60
-50
-40
-30
-20
-10
0
Temperature (C)
D
60°
208°
Redoubt
2009 03 23 13:30
0
2
5
8
10
13
km
2.2.0

Kelut 2014



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Data from BMKG