NOTICE

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Jonathan Lunine *

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AN AIRBORNE SYSTEM FOR DETECTION OF VOLCANIC SURFACE DEFORMATIONS (California Inst. of Tech.) 21 p HC A02/MF A01 CSCL 08K
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*Division of Geological and Planetary Sciences, California Institute of Technology
Pasadena, CA 91125

Abstract

A new technique is proposed for measuring volcanic deformations on the order of centimeters per day to centimeters per year, called the Airborne Radar Volcanic Surveillance System (ARVSS). Such a system would employ an airborne multifrequency pulsed radar, tracking passive ground reflectors spaced at 1 kilometer intervals over a 50 square-kilometer area. Identification of targets would be done by doppler and range resolution techniques, with final relative position measurements done by phase comparison of multifrequency signals. The system is impervious to all but severe weather, and can be operated day or night. Atmospheric path length errors may be corrected by an airborne refractometer, meteorological instruments, or other refractive -ivity measuring devices. Anticipated system accuracy is 1-2 cm, with measuring times on the order of minutes. Potential problems exist in the high intrinsic data assimilation rate required of the system to overcome ground backscatter noise.

Present geodetic techniques are too slow, cumbersome, and costly to be used on many remote volcanoes. Alternative proposed geodetic systems suffer from various drawbacks which make them unsuitable as volcanic deformation measuring tools. It appears that ARVSS satisfies all the requirements for such a tool.

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Introduction

The author worked during summer 1980 as a Visiting Graduate Fellow at Lunar and Planetary Institute, on the development of a remote sensing system for detection of volcanic surface deformations. As a Summer Intern in 1979, under the guidance of Drs. Stan Zisk and Tom McGetchin, the preliminary design of such a system was completed. This summer, with Zisk and Dr. Roger Phillips as advisors, an analysis of data processing requirements for the system, as well as a more definitive study of signal-to-noise requirements, were performed. As a result of these analyses, parameters such as reflector size, signal integration time, and effective bandwidth were determined for various system scenarios, which will form the basis for final system selection and hardware construction. Details on the system are contained in the draft of a report by Zisk and Lunine entitled "Airborne Radar Volcanic Surveillance System". A digest of the results from the report appears below.

The Problem

Ground surface deformations associated with volcanic activity are believed to be caused by subsurface magma movement. During active periods areas near the cone of a volcano may deform at a rate of centimeters per day, with areas on the flank moving at a rate of centimeters per year or slower. Measurement of such activity, to an accuracy of a centimeter or better, over a 50-100 square-kilometer area, is a major concern of a number of volcanologists. Magma chamber shape (Decker and Kinoshita, 1971) and lateral magma transport can be deduced from horizontal and vertical deformation data. The possibility also exists that such information can be used to predict eruptive or intrusive activity.

Present techniques for measuring volcanic deformations are all ground-based. Tiltmeters, while rapid and inexpensive, cannot give complete information on vertical and horizontal motion. Optical levelling provides vertical movement data to millimeter accuracy, but requires days to cover a 50 square-kilometer area, and is too costly to do frequently (Decker and Kinoshita, 1971). Relative horizontal movement is determined by ground electronic radio-ranging devices, which provide better than millimeter accuracy after atmospheric correction. Such ground-level devices suffer from line-of-sight difficulties, are time-consuming for a large reflector field, and are sometimes dangerous, as indicated by the death of a geologist performing such measurements on Mt. St. Helens at the time of the May 18, 1980 eruption.

Thus only a few volcanoes in Hawaii, Japan, and Iceland have been subjected to detailed and frequent deformation studies. A number of geologists have expressed the need for a relatively inexpensive tool for measuring volcanic crustal movements, with an accuracy in the range of one centimeter, and data collection times significantly less than a day. A number of current and proposed techniques, both ground-based and air/space-borne, have been devised by various groups for more general tectonic work, but none fits the requirements for a volcano-oriented system, based on analysis by the author. Thus an entirely new system, the Airborne Radar Volcanic Surveillance System (ARVSS), was designed by Zisk and the author to satisfy the requirements of volcanologists.

The System

ARVSS involves the placement of passive radar retroreflectors on the volcano of interest to form a reference grid, from which displacements of the surface can be detected. To adequately detail the ground movement, the reflectors would be spaced at 1 kilometer intervals, and cover roughly a 50 square-kilometer area (100 square-kilometers in larger rift systems). To achieve a high signal return over a broad angular range, the reflectors would be of the trihedral corner type, consisting essentially of two perpendicular specular bisecting planes. They would be anchored in the ground and covered with a protective foam enclosure to prevent coating by volcanic dust and water.

Remote detection of the passive retroreflectors would be performed by an airborne radar device, which would be flown over the volcano a sufficient number of times to detect all of the reflector grid points. Processing of the returned radar signal, for range and range rate (doppler) information, would yield the relative reflector positions to within meters, and phase comparison of the multifrequency signals would then provide the fine (1.5 cm) resolution of relative reflector positions. Performance of additional flyovers after a time interval ranging from days to months would reveal relative displacements in reflector positions, thus providing a direct measure of volcanic ground surface movements.

The type of radar, reflector size, and form of processing employed to provide the centimeter-scale accuracy required have been the subject of study by Zisk and the author. The results are summarized below. A flowchart of the analysis performed is shown in figure 1. The following are "constants" chosen for the system: A system frequency of 10 GHZ (X-band) has been selected for its short wavelength (hence high intrinsic accuracy--1-2 cm), and low water vapor signal attenuation (a problem for shorter wavelengths). A medium-sized carrier aircraft is assumed, based on user economic constraint, with a cruising altitude of 3 km. and a velocity of 0.0894 km./sec (200 miles/hr.). The velocity of signal propagation through the atmosphere, c, is set as 3.00 X 10^5 km./sec.

<u>Cell Area Calculation</u>: Consider a square trihedral reflector of panel length a. The cell area on the ground which must be resolved to detect the reflector is

$$\text{Cell AREA } A = \frac{8(0.7)\,a^4}{\lambda^2\, S/N\, \sigma_0} \qquad (1)$$

where

a=reflector panel length
λ =wavelength
S/N=signal-to-noise threshhold detection level
σ_0 =ground backscatter per unit area

Values of A for representative volcanic surfaces, incidence angles of the radar beam, and reflector sizes are shown in table 1.

<u>Doppler Resolution</u>: ARVSS resolves the ground into a matrix of cells. Doppler resolution fixes cell width in one direction, while antenna beamwidth or, if necessary, range resolution constrains the perpendicular direction. A study of

what could be achieved with doppler resolution was performed to determine whether range resolution would be required to limit cell size.

Consider the radar aircraft to be at the origin of a Cartesian coordinate system, the aircraft moving along the y-direction with a velocity $-v_y$. Then a reflector, placed at an arbitrary position in the coordinate system, may be seen to move with a velocity $+v_y$ in a frame initially coincident with the original coordinate system, but moving with the aircraft. This frame is shown in figure 2. Then

$$\text{Doppler Frequency} \quad f_d = \frac{2 y v_y f_0}{c(x^2+y^2+z^2)^{1/2}} \; ; \; f_0 = \frac{c}{\lambda} \tag{2}$$

As the aircraft moves along its path, the projections of the surfaces of constant doppler frequency on the ground form, for finite y, a family of proper hyperbolae. This can be seen by setting v_r, the radial velocity, and z constant, in an equation similar to (2) but expressed in terms of v_r rather than f_d. We get

$$y^2(v_r^2 - v_y^2) + v_r^2 x^2 + v_r^2 z^2 = 0 \tag{3}$$

which is the equation of a proper hyperbola for finite y (Korn & Korn, 1968). Hyperbolae of constant doppler are plotted in figure 3.

The change in doppler frequency with time is

$$\delta f_d \approx \frac{2 v_y^2 f_0}{c} \, \frac{x^2+z^2}{(x^2+y^2+z^2)^{3/2}} \, \delta t \tag{4}$$

which is plotted for various x and y in figure 4 (y_0 in the figure is the initial y-position of the aircraft--y is continually recalculated as t increases).

The doppler resolution cell width q (see figure 5), is a function of f_d and the doppler frequency spacing Δf_d. Explicitly:

$$|q| = \left| \frac{\Delta f_d}{f_d} \, \frac{z \sin\phi \cos\theta}{\sqrt{(\cos^2\phi \sin^2\theta + \cos^2\theta)^2 + \sin^2\theta \cos^4\phi \sin^2\phi}} \right| \tag{5}$$

Note that $q \propto \Delta f_d$. Values of f_d and q for $\Delta f_d = 2$ Hz are given in table 2.

Given the doppler cell widths shown in table 2, is range resolution necessary to achieve a cell size sufficiently small to permit target reflector detection? We consider a cell constrained in the range direction by the major axis of the projected beam on the ground (a "worst case"). Then

$$\text{CELL WIDTH IN RANGE DIRECTION} = \overline{pp} = \frac{2\sin(90-\frac{\psi}{2})}{\sin(90-\frac{\psi}{2}-\theta)} z \tan\frac{\psi}{2} \quad (6)$$

where ψ =antenna beamwidth, θ =beam's angle of incidence from vertical. Then $A=\overline{pp}\cdot q$, and from (1):

$$S/N = \frac{8(0.7)a^4}{\lambda^2 \sigma_o \overline{pp} \cdot q} \quad (7)$$

Values of S/N, for given θ , σ_o and q from tables 1 and 2, are given in table 3.

For a "reasonably-sized" reflector ($a \lesssim 0.5$ m), the S/N is much lower than the 15 dB required to detect the reflector. Thus range resolution (via multifrequency or pulsed radar) is needed to limit the range direction cell width to a size much smaller than is attainable by beamwidth limitation only. A 3 meter reflector can be detected within the beamwidth-limited cell, and several might serve as orienting points for the field, but such a complication will not be considered here.

<u>Range</u> <u>Resolution</u>: To detect the ½meter panel length reflectors requires, from equation (1), $A=25\ m^2$. For q=1 m, range cell width s must be 25 m. This requires a signal bandwidth

$$B = \frac{c}{2s} = 6 \times 10^6\ Hz \quad (8)$$

Assume a multifrequency CW (continuous wave) system. To avoid ambiguities in the signal return, the minimum frequency spacing within B must be

$$\Delta f_r = \frac{c}{2d} = 2 \times 10^4\ Hz \quad (9)$$

where d=aliasing (range ambiguity) distance, chosen to be the length of the reflector field (~ 7.5 km).

Then to achieve the effect of a random signal with the above minimum frequency spacing (300 such spacings spanning B),which is necessary to detect the reflector peak in the returned signal, 24 frequencies are required.* To achieve the fine resolution of 1.5 cm, 50 frequencies are required, for each of the 24. This is a prohibitively large number of frequencies from a practical standpoint. The

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*A "random signal" is created by selecting frequencies within the bandwidth with all possible spacings, from 20 KHZ up to the bandwidth. This requires 24 frequencies.

required number of frequencies can be drastically reduced by pulsing the radar signal.

Pulsed System Scenarios: Briefly, the processing scheme is as follows: compressed pulse signals, emitted from the airborne transmitter, bounce off the ground and are received by the aircraft. These signals are processed to provide rough resolution of the reflectors from doppler and range information. This is done at a number of frequencies simultaneously, which are then phase-compared to provide fine resolution of the reflectors' positions.

Three such systems are detailed in table 4. For the purpose of the analysis, a projected cell width (for the ½ meter panel length reflector) of 15 m^2, and projected doppler resolution of 4,2 Khz are considered. The equations used in the analysis are outlined below.

$$\text{BANDWIDTH } B = \frac{c}{2S} = \text{DATA SAMPLING RATE} \quad (10)$$

$$\#\text{ OF RANGE BOXES} = \frac{\text{REFLECTOR FIELD LENGTH}}{S} \quad (11)$$

$${}^{*}\text{PULSE COMPRESSION RATIO} = \frac{1}{\text{PULSE LENGTH} \cdot 2 \times f_{d\,max}} \quad (12)$$

FFT processing equations--To process the incoming signals, a Fast Fourier Transform (FFT) procedure is used. The number of samples per range box which must be taken to unambiguously detect the reflector signal is

$$\#\text{ OF SAMPLES/RANGE BOX} = \frac{2(2 f_{d\,max})}{\Delta f_d} \quad (13)$$

The FFT is not straightforward--as the aircraft moves along its path, reflectors will shift out of cells (slip) and processing must be done in frequency sections to avoid losing the reflector signal. The maximum doppler frequency which can be processed without slippage is

$$f_{ds} = \frac{S\,\Delta f_d}{d} \quad (14)$$

and processing must be done in frequency bins of width f_{ds}, from $-f_{d\,max}$ to $+f_{d\,max}$.

Finally: # OF MINIMUM FREQUENCY SPACINGS Δf FOR FINE

$$\text{RESOLUTION} \approx \frac{S}{1.5\text{cm}} \quad \text{(WHICH YIELDS REQUIRED NUMBER OF FREQUENCIES).} \quad (15)$$

Discussion: In each of the cases shown in table 4, recording rate demands are excessive, particularly for the 0.1 microsecond pulse system. Current tape devices

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* $f_{d\,max}$ IS THE MAXIMUM DOPPLER FREQUENCY GIVEN THE AIRCRAFT'S VELOCITY.

record at 60,000 megabytes/second, while fast computer memory storage and optical recording devices are currently prohibitively expensive for this application. Beaming the signals from the aircraft to ground recorders involves transmission complications which make this alternative impractical. The recording problem has not yet been solved.

The number of frequencies required for fine resolution is another system constraint. Over 3 times as many frequencies are required in the 0.1 microsecond pulse case as in the 0.01 microsecond pulse case. Onboard FFT processing to identify cells containing the reflectors (and hence reduce the number of cells which must be processed for fine resolution) is most easily done in the 3 meter reflector case. However, such a large reflector is not really a practical alternative. For the ½ meter panel length reflector case, the number of samples required for the FFT is excessive for the 0.1 microsecond pulse, and somewhat less so for the 0.01 microsecond pulse, primarily because of the reduction in the number of required frequencies. Although recording speed is very high in the 0.01 microsecond pulse mode, real-time processing need not be--one can record the returned pulse in 1/10 of a second, and then no pulses need be recorded over the remaining 9/10 of a second. Then the same amount of time is available for processing as in the 0.1 microsecond pulse case.

The problem of scintillation, or noise adding in phase in the reflected signal, was also analyzed, and found not to be a problem for the processing considered here.

Atmospheric refraction as a source of reflector position error has been examined. There are two components to this error: a stable "dry atmosphere" effect, and a highly variable water vapor influence. The latter may cause an apparent path length extension of up to 25 cm. A number of means of measuring the index of refraction or water vapor content of the air have been reviewed by the author. It appears that standard airborne meteorology equipment can correct for the effects to within 1-2 cm, and a new airborne refractometer developed in the Soviet Union by Levin, et al (1977) may provide correction to a centimeter.

Conclusion

Despite the fact that no clear-cut choice between the above pulse systems can as yet be made, and that serious recording rate problems exist in all cases considered, the system parameters which have been calculated indicate that the ARVSS type of deformation measurement can be performed. The measurement can be done day or night, in most weather, within the space of a half-hour. The use of passive reflectors eliminates the need for servicing visits to the observed volcano. Additional applications of the system include mapping of subsidence zones, saltdome deformation investigation for selection of nuclear waste disposal sites, and mapping of extraterrestrial volcanic deformations. The system's primary intended use, however, is in the measurement of terrestrial volcanic deformations, in areas inaccessable to current measuring devices.

References

Decker, R.W. and Kinoshita, W.T. (1971) Geodetic measurements. In The Surveillance and Prediction of Volcanic Activity: A Review of Methods and Techniques. Paris: UNESCO, p. 47-74.

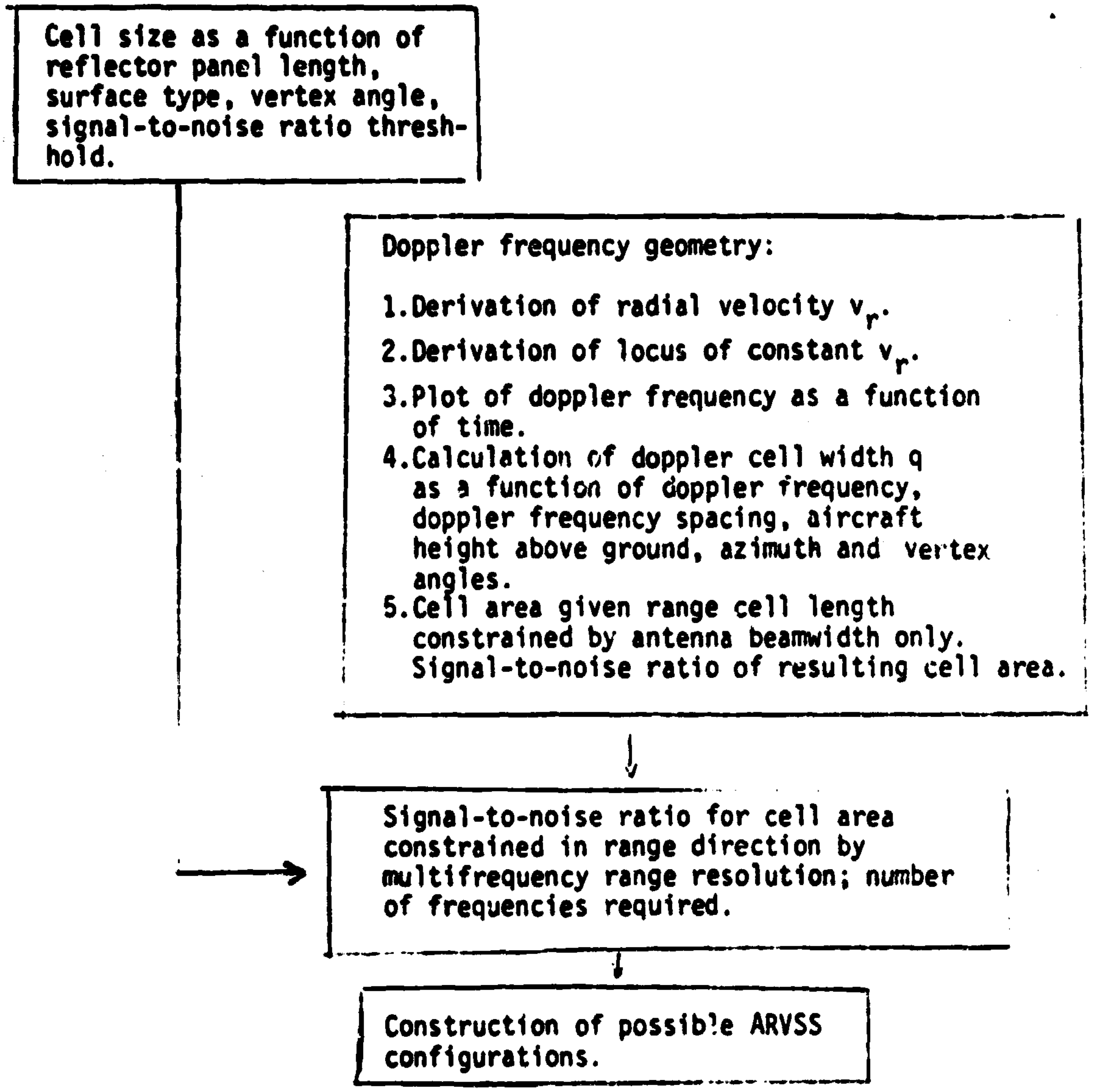
Korn, G.A. and Korn, T.M. (1968) Mathematical Handbook for Scientists and Engineers New York: McGraw Hill Book Co.

Levin, B.A., Proschechkin, N.K., Rotenber, M.I., and Rybarkov, K.I. (1977) Digital instrument for measuring the index of refraction of the atmosphere. Radio Engineering and Electronic Physics, 22, #9, 125-129.

Shultz, C.H., Oliver, T.L. and Peake, W.H. (1969) Radar Backscattering Data for Surfaces of Geological Interest . OSU ElectroScience Laboratory Technical Report 1903-7.

Figure 1 -

Flowchart of AR/SS Analysis



Cell size as a function of reflector panel length, surface type, vertex angle, signal-to-noise ratio thresh-hold.

Doppler frequency geometry:

1. Derivation of radial velocity v_r.
2. Derivation of locus of constant v_r.
3. Plot of doppler frequency as a function of time.
4. Calculation of doppler cell width q as a function of doppler frequency, doppler frequency spacing, aircraft height above ground, azimuth and vertex angles.
5. Cell area given range cell length constrained by antenna beamwidth only. Signal-to-noise ratio of resulting cell area.

Signal-to-noise ratio for cell area constrained in range direction by multifrequency range resolution; number of frequencies required.

Construction of possible ARVSS configurations.

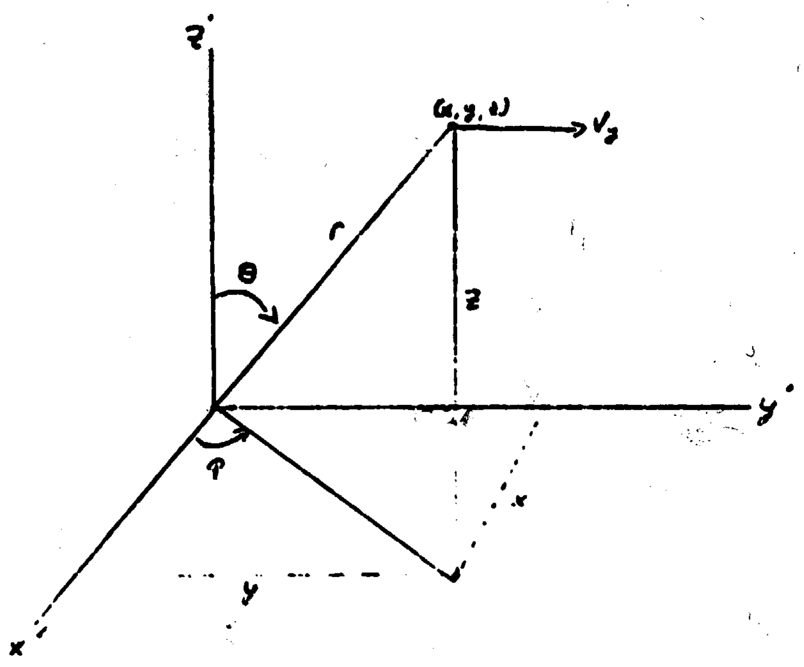
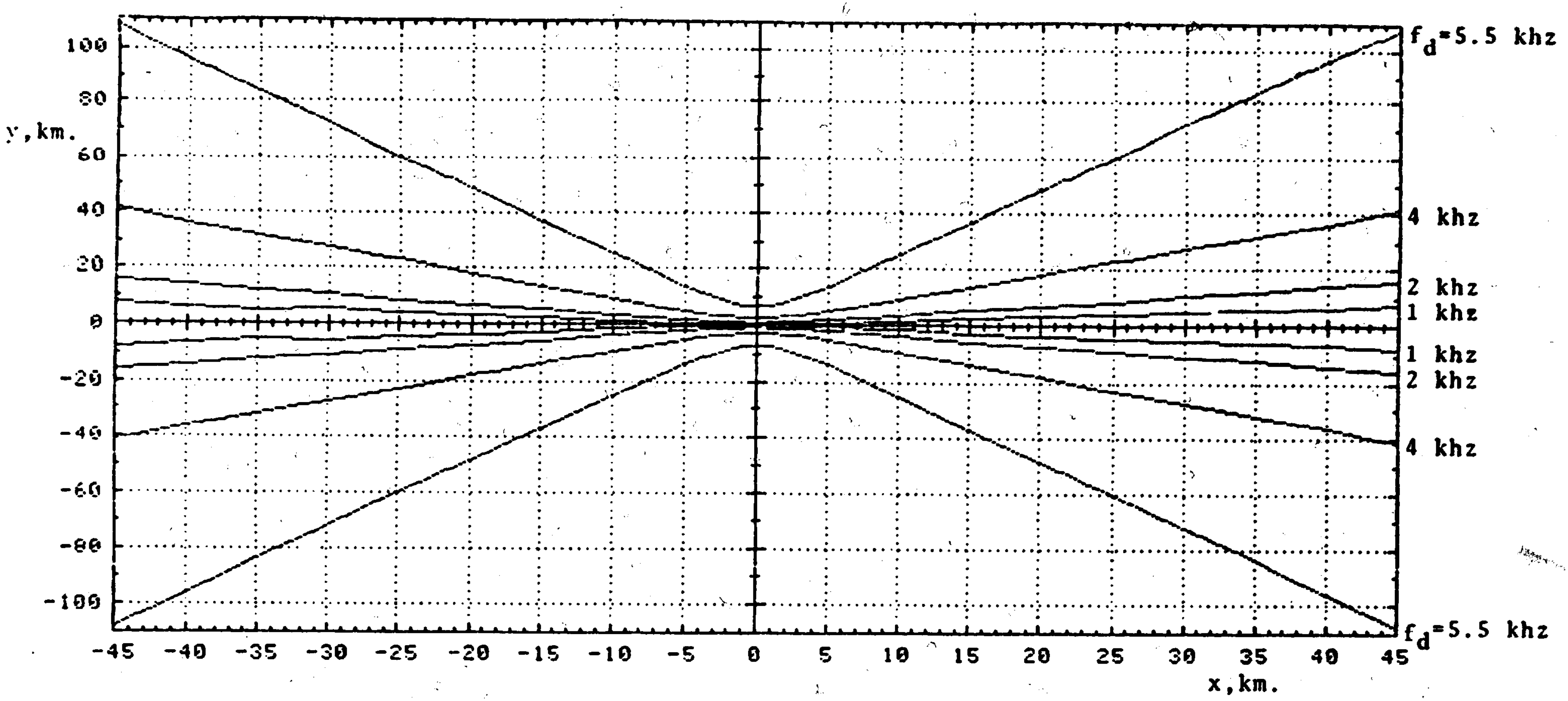


FIGURE 2



LOCI OF CONSTANT DOPPLER FREQUENCY

F_0=10GHZ
AIRCRAFT HEIGHT=3KM.
AIRCRAFT VELOCITY=0.0894 KM/SEC,VELOCITY VECTOR IN Y-DIRECTION

FIGURE 3

CHANGE IN DOPPLER FREQUENCY WITH TIME

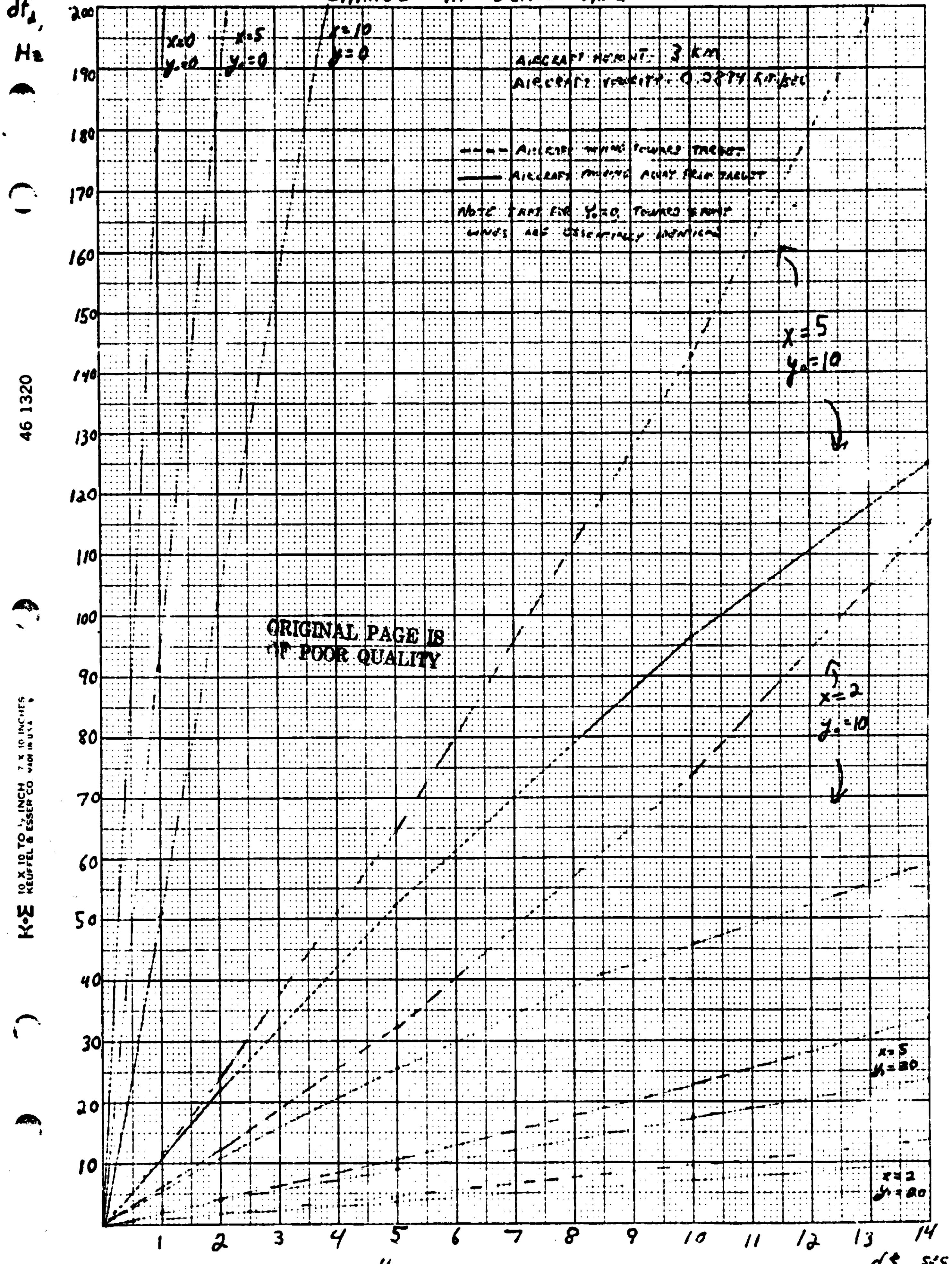


FIGURE 4

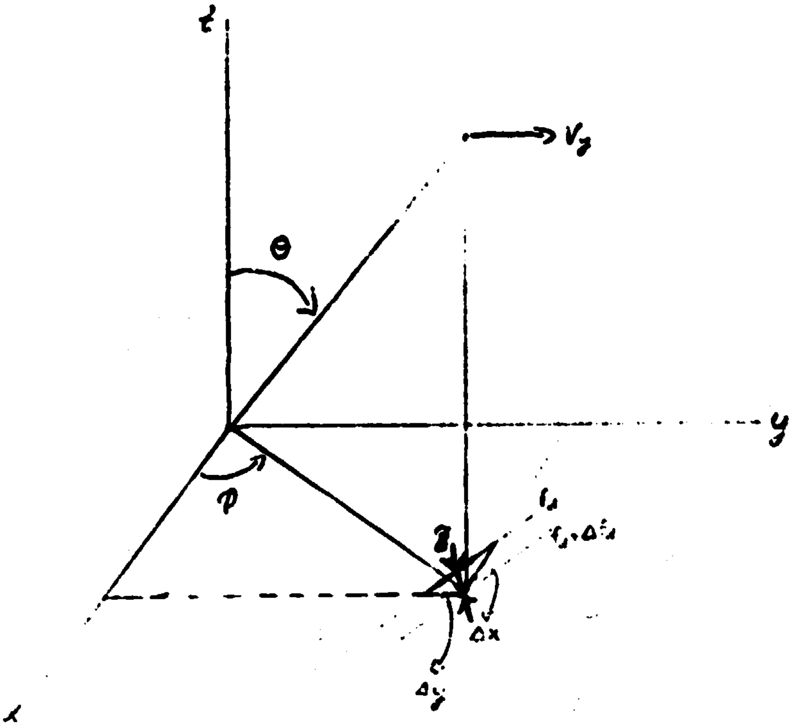


FIGURE 5

TABLE 1

CELL AREA (METERS^2) AS A FUNCTION OF TERRAIN BACKSCATTER AND REFLECTOR SIZE

$\lambda = 3$ cm, SQUARE TRIHEDRAL REFLECTOR,

		S/N = 15 dB							S/N = 5 dB				
LAPILLI SURFACE[1]													
θ	σ_0^+	a = 0.2	0.5	1.5	3	10 meters	θ	σ_0^+	a = 0.2	0.5	1.5	3	10 meters
10°	−7 dB	1.7	62	5000	7.8×10^4	9.6×10^6	10°	−7 dB	16	630	4.8×10^4	7.7×10^5	2.4×10^7
20	−9	2.3	92	7700	1.2×10^5	1.6×10^7	20	−9	25	760	7.8×10^4	1.2×10^6	1.7×10^8
30	−10	3.2	120	10000	1.6×10^5	1.9×10^7	30	−10	31	1200	9.6×10^4	1.2×10^6	2.0×10^8
40	−11	3.6	170	12000	2.0×10^5	2.5×10^7	40	−11	40	1500	1.2×10^5	2.0×10^6	2.6×10^8
50	−12	4.8	200	17000	2.5×10^5	3.1×10^7	50	−12	49	1900	1.6×10^5	2.6×10^6	3.2×10^8
60	−13	6.3	260	20000	3.1×10^5	4.0×10^7	60	−13	62	2500	2.0×10^5	3.2×10^6	4.0×10^8
70	−14	7.8	320	26000	4.0×10^5	4.9×10^7	70	−14	77	3000	2.5×10^5	4.0×10^6	4.8×10^8
PUMICE SURFACE[1]													
θ	σ_0^+						θ	σ_0^+					
18	−4 dB	0.77	30	2500	4.0×10^4	48×10^6	18	−4 dB	7.8	320	2.6×10^4	4.0×10^5	4.9×10^7
20	−5	0.92	38	3100	4.8×10^4	6.3×10^6	20	−5	10.	400	3.2×10^4	5.0×10^5	6.7×10^7
30	−8	2.0	77	6200	1.0×10^5	1.2×10^7	30	−8	20.	780	6.3×10^4	1.0×10^6	1.2×10^8
40	−9	2.3	92	7700	1.2×10^5	1.6×10^7	40	−9	25	960	7.8×10^4	1.3×10^6	1.7×10^8
50	−11	3.6	170	12000	2.0×10^5	2.5×10^7	50	−11	40	1500	1.2×10^5	2.0×10^6	2.6×10^8
60	−11	3.6	170	12000	2.0×10^5	2.5×10^7	60	−11	40	1500	1.2×10^5	2.0×10^6	2.6×10^8
PAHOEHOE SURFACE:													
θ	σ_0^*						θ	σ_0^*					
25	+3	0.15	6.3	480	7.7×10^3	9.8×10^5	25	+3	1.7	62	5.0×10^3	7.8×10^4	9.6×10^6
25	0	0.31	12	1000	1.7×10^4	2.0×10^6	25	0	3.2	120	1.0×10^4	1.6×10^5	1.9×10^7
25	−2	0.50	19	1600	2.6×10^4	3.2×10^6	25	−2	4.8	200	1.7×10^4	2.5×10^5	3.1×10^7

+ = HORIZONTAL POLARIZATION

* = VERTICAL POLARIZATION

θ = ANGLE FROM VERTICAL

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[1] RANGE OF GROUND BACKSCATTER VALUES (σ_0) ALSO COVERS UPPER LIMIT OF σ_0 FOR SMOOTH BASALT AND AA SURFACES. σ_0 DATA FROM SCHULTE, ET AL, 1969, P. 16, 23, 46, 47

FOR TRIANGULAR TRIHEDRAL REFLECTOR, MULTIPLY A VALUES BY 0.25

TABLE 2

f_d AND q AS FUNCTIONS OF φ, θ

$\bar{r}$ = 3 Km

Δf_d = 2 Hz ($\Rightarrow$ minimum q contains entire ½-meter pixel length resolved)

V_y = 200 miles/hour = 0.0894 km/sec

c = 3×10^5 km/sec

φ	θ	f_d Hz	q meters
0	5	0	1.01
	15	0	1.04
	30	0	1.16
	45	0	1.42
30	5	260	1.01
	15	771	1.06
	30	1490	1.23
	45	2110	1.58
45	5	367	1.01
	15	1090	1.08
	30	2110	1.32
	45	2980	1.80
60	5	450	1.03
	15	1336	1.10
	30	2581	1.42
	45	3650	2.16
90	5	517	1.02
	15	1540	1.12
	30	2980	1.55
	45	4214	2.84

TABLE 3

S/N FOR RESOLUTION CELLS CONSTRAINED IN RANGE DIRECTION BY ANTENNA BEAMWIDTH

$\Delta f_d = 2 Hz$
$\psi = 45°$
$\varphi = 0°$
$z = 3 Km$

θ	$\overline{R_t}$, Km	A ($\times 10^3$ m)	S/N: (dB)			
			a = ½ METER		a = 3 METERS	
			LAPILLI	PUMICE	LAPILLI	PUM
15	0.578	3.02	−0.900	−5.91	30.2	25.2
30	0.754	4.38	−0.520	−2.56	30.6	28.6
45	1.20	8.54	−1.91	−3.41	29.2	27.7

TABLE 4

SYSTEM PARAMETERS FOR ALTERNATIVE REFLECTOR SIZES + PULSE LENGTHS

PARAMETER	¼ METER REFLECTORS		3 METER REFLECTO
PULSE LENGTH	0.1 μsec	0.01 μsec	0.1 μsec
REQUIRED RESOLUTION CELL AREA	15 m²	15 m²	14,000 m²
RANGE RESOLUTION/FREQUENCY	15 m	1.5 m	15 m
# OF RANGE BOXES	500	5000	500
DOPPLER FREQUENCY RESOLUTION	1 Hz	10 Hz	933 Hz
PULSE COMPRESSION RATIO	1200:1	12,000:1	1200:1
# OF FREQUENCIES REQUIRED FOR FINE RESOLUTION	45	14	45
DATA RECORDING (SAMPLING RATE) PER FREQUENCY	10 MHz	100 MHz	10 MHz
FFT PROCESSING			
# OF SAMPLES/FREQUENCY	17,000 SAMPLES/RANGE BOX	1700 SAMPLES/RANGE BOX	18.0 SAMPLES/
MAXIMUM DOPPLER FREQUENCY TO AVOID SLIPPAGE	1000 Hz	1000 Hz	466,500 Hz
# OF SEPERATE FFT PROCESSORS REQUIRED TO AVOID SLIPPAGE	9	9	1