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INTRODUCTION

The Yellowknife Seismic Array (YKA) was established in 1962 by the Department of Energy, Mines and Resources (then Mines and Technical Surveys) in cooperation with the United Kingdom Atomic Weapons Research Establishment (Manchee and Somers, 1966). The array centrepoint (CP) was located by a Department of Public Works survey party; true north was determined by star shots and the East-West and North-South axes were laid out as precisely as possible. Later a Canadian Army Survey team ran a tellurometer and theodolite loop around the extremities of the array and tied the CP and several other positions to the geodetic bench marks in the area. The seismometer vaults were constructed as near as possible to their surveyed positions, limited by the availability of bedrock. Certain vaults were later relocated because of drainage problems. Toward the end of 1968, during the evaluation of a seismic calibration experiment, it was suspected that consistent arrival time residuals might partially be caused by small mislocations of the array seismometers. To obtain accurate positions for all present seismometer vaults, a photogrammetric survey was therefore made. Using low level air photography in conjunction with an available airphoto series, precise Universal Transverse Mercator co-ordinates (UTM) and elevation estimates were obtained for all present vault positions. This paper presents the results of the recent survey.

PROCEDURE AND RESULTS

The Yellowknife technical staff located the positions of each of the 19 active seismic vaults on regular aerial survey photographs (Roll A 18132-Spartan Air Services Contract 63-37, 1000 feet = 1 inch). To aid in the site identification, low-level Polaroid air photos of every vault were taken during the winter of 1968-69, after the vault locations had been marked by a cross of black tar paper laid on the snow surface. Vault locations were marked by pin holes in the Spartan air photos. The estimated precision of location is thought to be about the size of the pinhole, about 0.3 mm. At the average scale of these photos of 1:12000 this amounts to an accuracy of better than 4 metres. The photos were submitted to the Special Projects section of the Topographical Survey, Department of Energy, Mines and Resources, where the UTM co-ordinates and elevations for each vault were derived. The results are listed in Table I. The table also includes geographic co-ordinates for all vaults, which have been calculated by the Topographic Survey from the UTM co-ordinates, using Clarke's 1866 geoid.

Table II summarizes the differences between the original and 1968 surveys in a convenient way: the absolute differences in latitude and longitude in seconds of arc are tabulated for the 12 vaults included in the original survey. The new co-ordinates are significantly different from the old, having the effect of moving the average vault location 51 metres north and 56 metres west of the 1962 location. Seismologically this absolute shift should be negligible for all purposes, except for very short range crustal experiments. The small average elevation difference is irrelevant seismically. The

Table I

YELLOWKNIFE ARRAY, SEISMOMETER SITES, ZONE 11
SPECIAL PROJECT, TOPOGRAPHIC SURVEY, OTTAWA, 1969

Seismometers	Easting	Northing	Latitude	Longitude	Elevation	
	(m)	(m)	(N)	(W)	(ft)	(m)
B1	623747.4	6921100.6	62° 24' 8.64"	114° 36' 19.61"	565.9	172.5
B2	623656.0	23593.9	25 29.24	19.53	590.5	180.0
B3	623568.8	26248.0	26 55.03	18.75	615.6	187.6
B4	623489.3	28748.4	28 15.85	17.83	633.0	192.9
B5:CP	623380.0	31215.3	29 35.62	19.07	645.4	196.7
B6	623299.5	33809.1	30 59.46	17.97	664.6	202.6
B7	623191.9	36313.3	32 20.44	19.00	670.5	204.4
B8	623129.3	38825.8	33 41.62	16.86	649.4	197.9
B9	623083.6	41209.4	34 58.63	13.86	699.3	213.1
B10	622928.0	43766.2	36 21.36	18.11	726.9	221.6
R1	605854.2	6930555.2	29 33.81	56' 44.10"	557.6	170.0
R2	608386.2	30643.2	34.02	53' 47.13	574.0	175.0
R3	610894.6	30748.3	34.74	50 51.78	580.1	176.8
R4	613379.0	30805.1	33.87	47 58.21	568.8	173.4
R5	615929.6	30953.0	35.81	44 59.80	600.0	182.9
R6	618431.7	31045.7	35.96	42 04.91	630.5	192.2
R7	620888.0	31139.7	36.14	39 13.21	652.4	198.9
R8:CP	623379.9	31215.2	35.62	36 19.08	645.2	196.7
R9	625932.6	31301.4	35.32	33 20.68	659.7	201.1
R10	628362.5	31391.7	35.23	30 30.84	672.4	204.9
Least Squares Common point	623395.	6931220.	62° .49327	114° .60500	643	196.0
B5 = R8	623380.	6931215.	62° .49323	114° .60530	645	196.7
CP, 1962 Survey			62° .49293	114° .60426	639	195.0

relative position differences are generally small, but are too large for the accuracy originally claimed for this survey. No attempt has been made to correlate the differences with vault relocations during the past six years.

Table II

ABSOLUTE AND RELATIVE CHANGES OF VAULT CO-ORDINATES

	Absolute Change			Relative Change*	
Vault**	Latitude	Longitude	Elevation	Latitude	Longitude
	(inches)	(inches)	(feet)	(inches)	(inches)
B3	-3.9	2.8	5	-5.6	-1.1
B4	2.1	0.7	4	0.4	-3.2
B6	3.2	3.0	4	1.5	-0.9
B7	1.8	2.7	5	0.1	-1.2
B9	0.4	3.1	0	-1.3	-0.8
R2	0.7	7.6	7	-1.0	3.7
R4	1.6	4.8	-11	-0.1	0.9
R6	1.4	4.6	12	-0.3	0.7
R7	1.4	3.2	12	-0.3	-0.7
R8	1.3	2.6	10	-0.4	-1.3
R9	1.2	6.1	5	-0.5	2.2
R10	0.9	6.1	-11	-0.8	2.2
Average	1.7	3.9	rms	.96	1.9
	(51m)	(56m)		(30m)	(27m)

*Relative = Absolute - average. **The vaults not listed in this table were not tied into the original survey.

In the interpretation of seismological data, least-squares analysis is frequently applied, e.g., the least-squares fitting of an ideal wavefront to the seismometer positions for measurement of $dT/d\Delta$. To make the data in Table I more amenable to a seismological interpretation, the vault positions were therefore fitted by least squares. Since the UTM grid is only slightly rotated from true north, this Cartesian system was first used for two fits per line, one in northing and one in easting. Table IIIa gives the least-squares parameters for the NS (Blue) and EW (Red) lines and Table IIIb lists the deviation of all vaults from these least-squares lines to the nearest metre. The convergence angle between grid and true north at the array centre-point is calculated from $\gamma = (117^\circ$ -longitude (CP)* sin (latitude (CP)), using geocentric latitude. Because of the small value of γ, 2.124°, the seismometer deviations have not been converted into meridional and vertical (EW) components. The co-ordinates of the least-squares common point in Table I were obtained by averaging the component deviations of B5 and R8 and adding to the B5 = R8 location: the error incurred is 4 metres, which is about the estimated relative precision of the present survey.

The bearing of the Red Line great circle segment is only E0.03°N at the geometric centrepoint, negligible for seismic purposes. However, the bearing of the Blue Line is N0.12°E, and this should be taken into account for research projects. The fact that it is so large requires comment; the azimuth of the surveyed NS line was given as 0.098 second of arc, which is considered to be negligible. However, the old B9 position is 216 feet east, and the old B3 and B4 are respectively 33 and 83 feet west of the surveyed line. This amounts to about 100 in 15,000 metres, or approximately 0.4°. Thus the present least squares bearing is actually smaller than the old "eyeball" bearing.

Instead of computing components of $dT/d\Delta$ independently for the two seismometer lines, a least-squares plane is often fitted simultaneously to all arrival times. In writing the corresponding computer program, it was assumed that the array arms are orthogonal, equispaced, and intersect at the ideal B5 and R8 positions. These assumptions will lead to location residuals different from those in Table III. They are listed in Table IVb, while IVa gives the least-squares parameters for this orthogonal, equidistant crossed array. The deviation from the precise NS orientation is negligible. The simultaneous fit has rotated the NS line more than EW line because of the asymmetry of the cross.

For ease of programming this computation, the centrepoint seismometer has been included in either line. Clearly, different assumptions or different weights would lead to special sets of geometric residuals. These would, for instance, be relevant for a least-squares planar fit with one or several seismic channels out of operation.

One special set of geometric residuals is given in Table V. These are the deviations from the ideal orthogonal, NS oriented, 2500 metre spaced array.

The principal radii of curvature at the centrepoint, given in Table III, were calculated using Fisher's 1960 geoid; to the needed precision the difference from Clarke's 1866 geoid is immaterial. For conversion from linear measurement of $dT/d\Delta$ (ms/km) to geocentric measure (s/degree), as customary in seismology, the earth's

Table III

LEAST SQUARES LINE PARAMETERS AND RESIDUALS

Least Squares Site Separations								
	Northing (m)	Easting (m)	Meridional Distance (m)	Meridional Distance (degrees) (geocentric)	Vertical Distance (m)	Vertical Distance (degrees) (geocentric)	Azimuth (degrees)	Elev. (m) (N&E up)
Blue Line	2518.0	-88.2	2519.6	0.022693	5.		0.12	4.6
Red Line	94.3	2502.2	1.		2504.0	0.022536	89.97	4.1

Least Squares Site Residuals (metres)

Vault	Northing	Easting	Elevation
B1	-51	3	- 3
B2	-76	0	- 1
B3	60	1	2
B4	42	10	3
B5	- 8.7	-11.5	- 2
B6	67	- 4	3
B7	53	-23	1
B8	48	2	-11
B9	-87	45	0
B10	-48	-22	4
R1	0	-30	1
R2	- 6	0	2
R3	4	7	0
R4	-33	-12	- 7
R5	20	37	- 2
R6	19	37	3
R7	18	- 9	6
R8	- 0.5	-19.3	- 1
R9	- 9	31	- 1
R10	-13	-41	- 1

Reciprocal principal curvatures for CP: 111.46 km/deg. meridional, 111.62 km/deg. vertical. Radius =6361.6 km. (111.03 km/deg.). Azimuth of UTM grid-north at CP 2.124°.

Table IV

LEAST SQUARES ORTHOGONAL, EQUIDISTANT CROSS

Parameters		
Distance between vaults		Azimuth of NS Line
(m)	(degrees) (geocentric)	(degrees)
2510.4	0.022610	0.004

Site Residuals (metres)		
Vault	Northing	Easting
B1	- 85	-29
B2	-100	-27
B3	45	-22
B4	37	- 8
B5	- 5.0	-24.7
B6	80	-12
B7	76	-27
B8	79	3
B9	- 46	50
B10	2	-12
R1	- 15	10
R2	- 20	34
R3	- 8	33
R4	- 44	9
R5	11	51
R6	11	44
R7	12	- 8
R8	- 5.1	-24.8
R9	- 12	19
R10	- 14	-60

radius at CP should be used instead of the radii of curvature. The corresponding conversion factor is also given in Table III.

CONCLUSION

The 1968 airphoto survey has supplied a new set of relative co-ordinates for the presently established seismic vaults of the Yellowknife array. The relative precision of the survey is thought to be about 4 metres. The average absolute array location was found to be about 75 metres northwest of the one formerly established. Since the former ground survey was carefully tied to a geodetic bench mark in the area, the old absolute co-ordinates are preferred for the centrepoint; they are 62.49293° N and 114.60426° W. For relative measurements, however, the new survey is preferred,

Table V

RESIDUALS RELATIVE TO NS ORIENTED, 2500m SPACED ARRAY

Vault	Northing	Easting
		(m)
B1	-129	-15
B2	-134	-14
B3	22	- 8
B4	24	5
B5	- 7.4	-11.6
B6	88	1
B7	94	-14
B8	108	16
B9	- 6	63
B10	52	0
R1	- 19	-49
R2	- 24	-16
R3	- 11	- 6
R4	- 47	-20
R5	8	33
R6	8	37
R7	10	- 5
R8	- 7.5	-11.7
R9	- 14	43
R10	- 16	-26

since it gives locations for seven seismic vaults not included in the former survey, and gives new locations for vaults since moved. The deviations of some vaults from straight least-squares lines are generally small, but should contribute statistically to observed residuals in seismic arrival times.

The NS (Blue) Line and EW (Red) Line bear N0.12°E and E0.03°N, respectively, and the least-squares distances between seismometers are within 1 per cent of the nominal 2500m (2520m on the Blue Line and 2502m on the Red Line). A least-squares, orthogonal, equispaced cross fitted to the vault positions bears N0.004°E and has an average spacing of 2510.4 metres. The contribution to the error in the measurement of $dT/d\Delta$ arising from the neglect of these deviations from the nominal values are smaller than errors arising from other causes. The results of past calculations which assumed an orthogonal equispaced, exactly NS - oriented array, are therefore not significantly altered and previous conclusions remain valid.

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