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DEPARTMENT OF TRANSPORT
METEOROLOGICAL BRANCH

AN ANALYSIS OF THE
METEOROLOGICAL CONDITIONS
DURING A CASE OF SEVERE
TURBULENCE

BY
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CANADA - DEPARTMENT OF TRANSPORT - METEOROLOGICAL BRANCH
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AN ANALYSIS OF THE METEOROLOGICAL CONDITIONS DURING
'A CASE OF SEVERE TURBULENCE', MAY 6TH, 1963

by

S. J. Buckler

ABSTRACT

This is a detailed study of the causes of a case of severe turbulence encountered in the lee of the Canadian Rockies at 21,000'. Analysis of the meteorological conditions indicate a standing wave situation with a wavelength of 8 miles. Terrain features on the airway of the same wavelength magnified the amplitude of the standing wave, resulting in drafts greater than 5000 ft. min^{-1} . The aircraft entered the stationary wave while flying downstream with a ground speed of 482 knots. The conclusion is reached that the principal factor in the severity of the jolt was the speed of entry into the wave downdrafts. Reducing the aircraft's airspeed would not reduce the entry speed sufficiently to avoid damaging accelerations, nor would aircraft flying upwind encounter the same severity.

ANALYSE DES CONDITIONS MÉTÉOROLOGIQUES DANS LE CAS D'UNE
FORTE TURBULENCE RENCONTRÉE LE 6 MAI 1963

par

S. J. Buckler

RÉSUMÉ

Ceci est une étude détaillée des causes de la forte turbulence rencontrée à 21,000 pieds, du côté sous le vent des montagnes Rocheuses. L'analyse des conditions météorologiques a révélé la présence d'une onde stationnaire d'une longueur d'onde de 8 milles. Les accidents de terrain, sous la voie aérienne, étant de la même longueur d'onde ont augmenté l'amplitude de l'onde stationnaire; il en est résulté des courants d'air de plus de 5,000 pi/mn^{-1} . L'aéronef a pénétré dans l'onde stationnaire alors qu'il volait vent arrière à une vitesse-sol de 482 noeuds. On en est venu à la conclusion que la principale cause de la violence de la secousse a été la vitesse d'entrée dans les courants descendants de l'onde. Dans un cas de ce genre, une diminution de la vitesse propre de l'aéronef ne réduirait pas suffisamment la vitesse d'entrée pour empêcher des accélérations dommageables. Par contre, un aéronef volant vent debout ne subirait pas de secousse aussi forte.

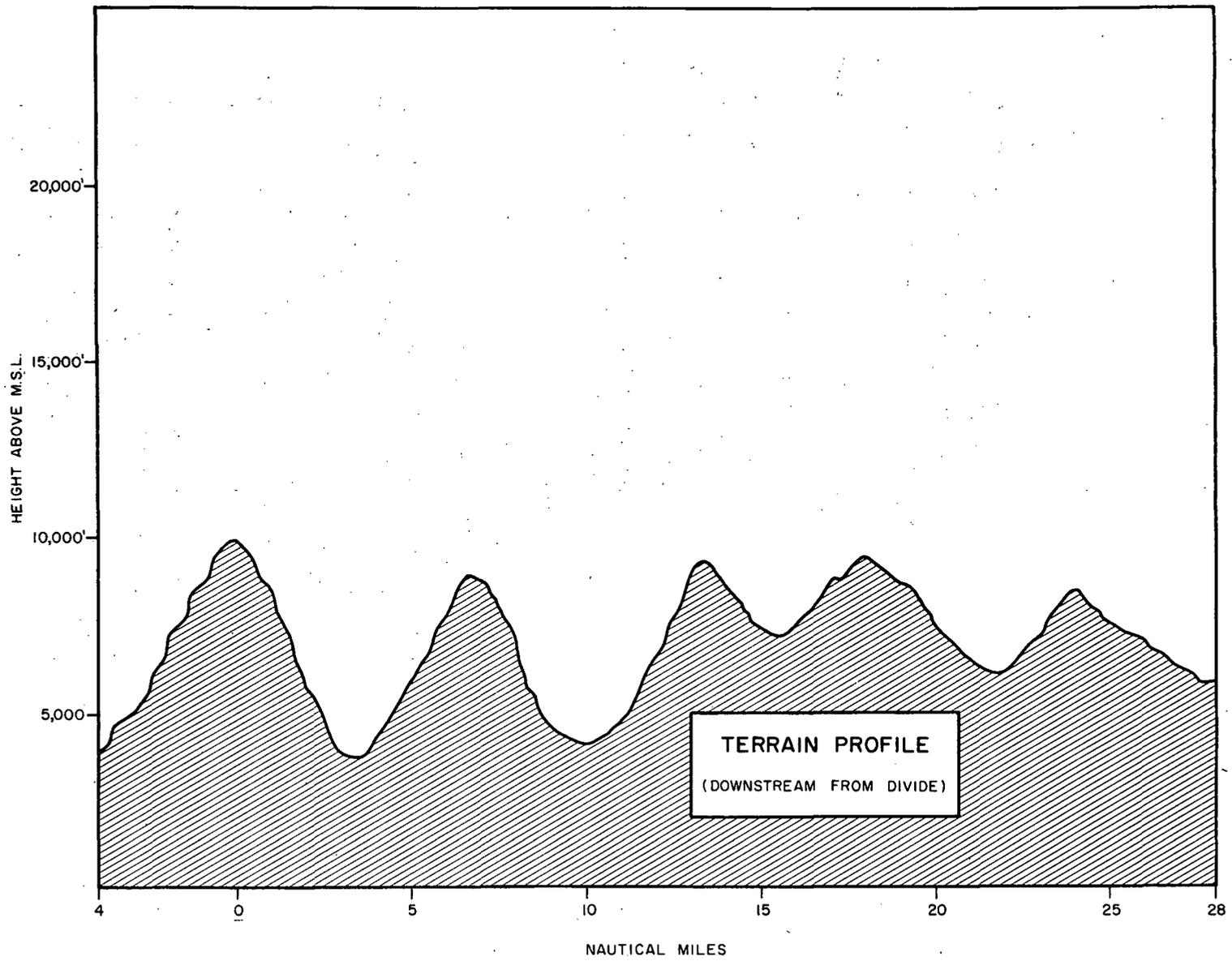


Figure 1

AN ANALYSIS OF THE METEOROLOGICAL CONDITIONS DURING
A CASE OF SEVERE TURBULENCE, MAY 6TH, 1963

by

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1. On May 6th, 1963, TCA Flight #502-6 experienced 2 severe jolts while flying at 21,000 feet over the Divide between Vancouver and Edmonton. The pilot estimates that the aircraft plunged 800 ft. in 3 to 5 seconds, followed by a choppy interval, and then a second violent descent. Three seats were pulled loose in the cabin. Passengers with unfastened seat belts were injured. Roof panels were bent and displaced when passengers were thrown upwards. Some seat mountings were broken. This occurred at 1815Z between Rocky Mountain House and the Divide.

This report is an exploration of the meteorological factors involved in the incident. It presents a reasonable explanation for the vertical currents encountered by Flight 502.

2. PARTICULARS OF THE FLIGHT

Equipment and Route Terrain

The equipment operating as Flight 502 was a Vickers Vanguard. This plane, at 21,000 ft., has a cruising speed of approximately 360 kt. The route from Vancouver to Edmonton was flown via designated airway Red 75 through Enderby and Rocky Mountain House to Edmonton. The height of the main range of the Rockies here is near 10,000 ft. with several peaks over 11,000 ft. Immediately east of the Divide, the terrain drops sharply to 5,000 ft. or less. A number of ridges from 8,000 to 9,000 ft. above MSL are spaced about 6-7 miles apart, at right angles to the flight path, and immediately east of the main range. A schematic outline of the terrain east of the divide is shown in Fig. 1.

Flight Conditions

The pilot reported the corrected air temperature at 21,000 ft. as -26°C and his tail-component as +151 kt. He

described the weather as sunny and that he was occasionally in thin altocumulus or altostratus. This may well have been altocumulus lenticularis since Pincher Creek reported AC/CI LENT for several hours before and after 1800Z. Pincher Creek is 150 miles southeast of the route under study, but it is also immediately east of the same range of the Rockies. The staff at Pincher Creek is particularly conscious of lenticular cloud formations because several sail-plane meets have been held there. Heights of the clouds were estimated as 19,000 and 35,000 ft. respectively above terrain. This would then fit the thin altocumulus at 21,000 MSL reported by 502.

Sequence of Events Leading to the Severe Jolts

Apparently some preliminary motion of the aircraft caused the captain to reduce power and to order seat belts fastened. The captain mentioned "subsidence" in this regard. An engineer passenger described "several undulations" prior to the order to fasten seat belts. Before the effect of reducing airspeed could be felt, or before all seat belts could be fastened, the aircraft experienced a severe jolt. The pilot estimated a drop of 800 ft. in 3 to 5 seconds. This was followed by a short choppy interval and then a second severe jolt or drop of unspecified magnitude.

3.

METEOROLOGICAL SITUATION

Synoptic Picture

At the time of the flight the surface chart for May 6, 1800Z (Fig. 2), showed a maritime Arctic cold front on a NE-SW line from southeast of Penhold to Kimberley, Spokane, and Medford, moving southeast about 13 kt. The jet stream associated with this front was also oriented on a NE-SW line between Edmonton and Vancouver. Height of the jet core was near 30,000 ft. The axis of the jet is shown on the 300-mb chart for May 6, 1200Z (Fig. 3). It is apparent that the jet-stream axis is parallel to the flight path of 502. The history of the 300-mb analysis showed that the axis of the stream was drifting slowly southeast at about 10 kt. A jet maximum of 150 kt is noted near Vancouver. This maximum propagated northeast along the jet stream at 35 kt to a position just west of the Divide at 06 1800Z and to near Edmonton at 070000Z.

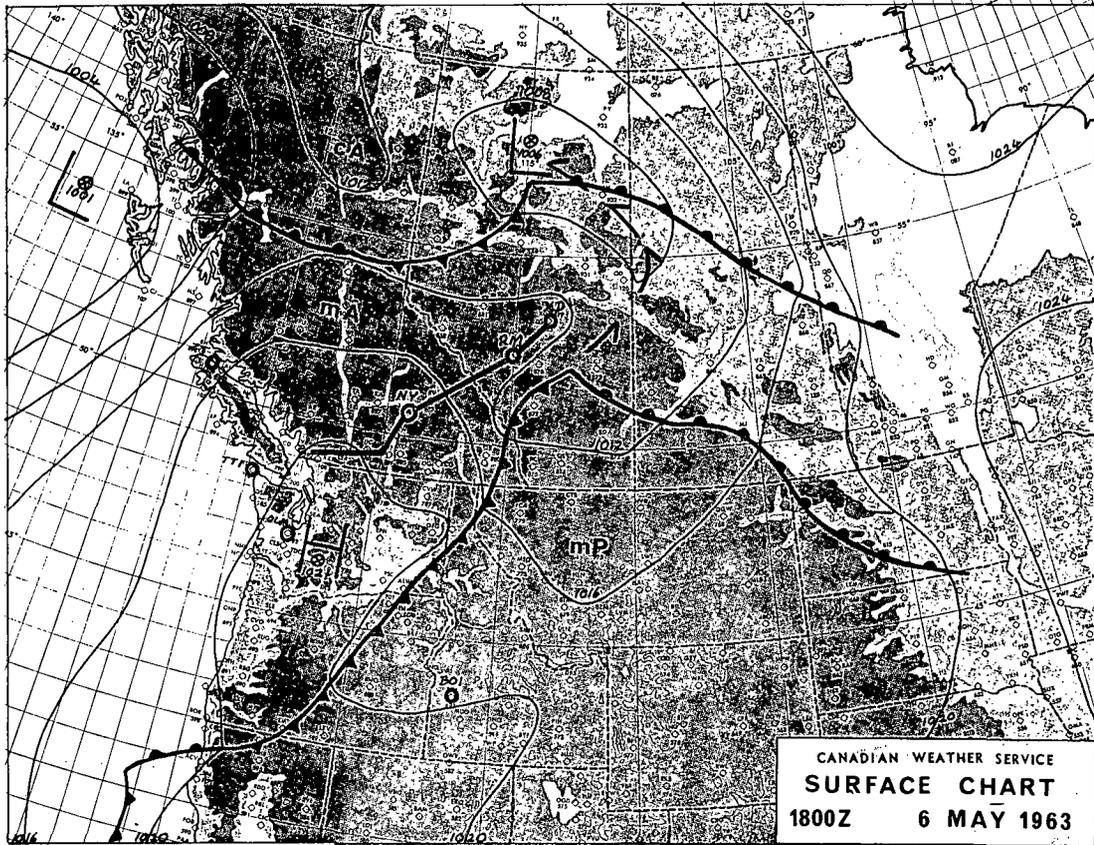


Figure 2

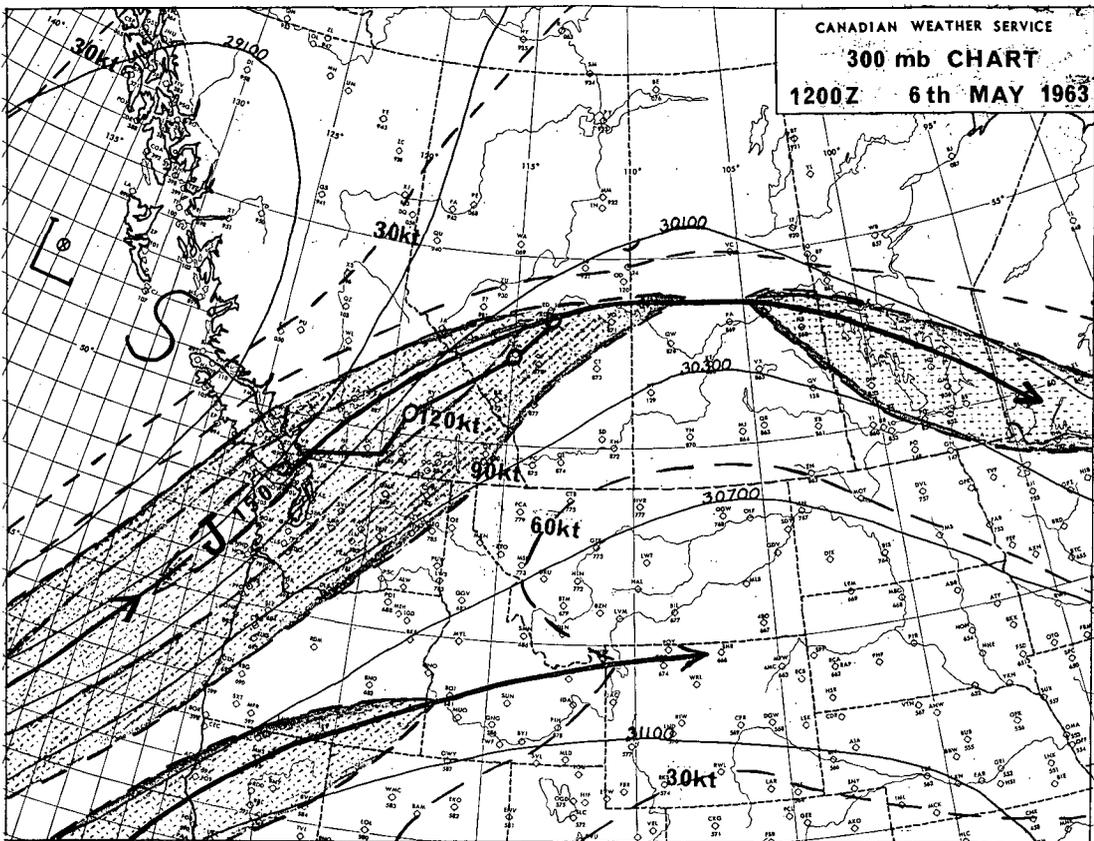


Figure 3

Frontal Cross-section Over Flight Route

The effect of the cold-frontal surface was to produce an isothermal or stable layer over the flight route. Height of the stable layer varied with distance from the surface position of the front. Fig. 4 shows plotted tephigrams for three ascents through the frontal surface. A cross-section through the front was constructed (Fig. 5) to show the wind structure. Ascents from Port Hardy, Tatoosh, Olympia, Spokane, and Boise, for 061200Z were used. These stations form a line at right angles to the jet stream and only a short distance downstream from the location of the jet maximum at 1200Z. Since the jet maximum was moving downstream and lay just west of the Divide at 1800Z, the cross-section must represent very closely conditions near the Divide at the time of the turbulence reported by 502. The exact meso-scale construction of the jet is always uncertain, but the flight report of a wind component of 142 kt. fits the cross-section construction. It is to be remembered that 502 had flown through the jet maximum and so would be reporting a tail component somewhat larger than shown in the cross section at 21,000 ft.

Wind Shear Extremes in Vicinity of Route

Because of the pronounced temperature gradient through this front, strong vertical wind shears obtained. Hodographs for Olympia and Tatoosh at 061200Z show wind shears of 20 and 21 kt in 2,000 ft. intervals over Olympia and as great as 48 kt. in 2,000 ft. over Tatoosh. Such wind shears are found near jet cores. A British study suggests that the latter figure may be reached no more than 2% of the time for a 2,000 ft. layer. Attention is drawn to this point because of the association of high-level turbulence with intense vertical wind shear.

Wind Direction

The main ridge of the Rockies crosses the flight path on a line oriented from 325° to 145°. The direction of flow in the jet stream is 210° to 220° which is almost perpendicular to the main ridge. This is an important consideration in the establishment of a standing wave as discussed below. It should also be noted that the direction of flow is also parallel to Red 75

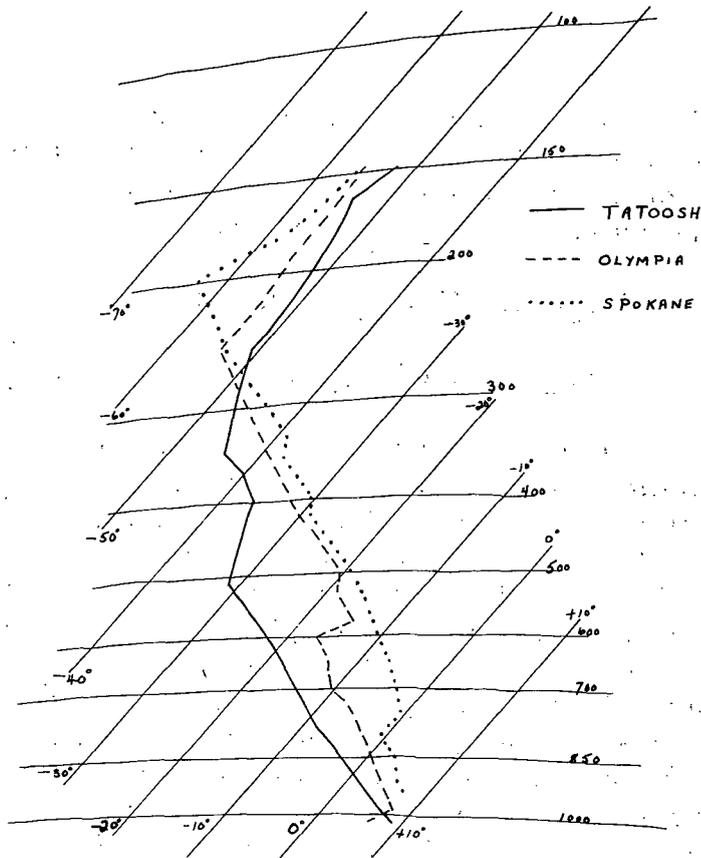


Figure 4
Upper Air Soundings For Tatoosh, Olympia and Spokane at 061200Z

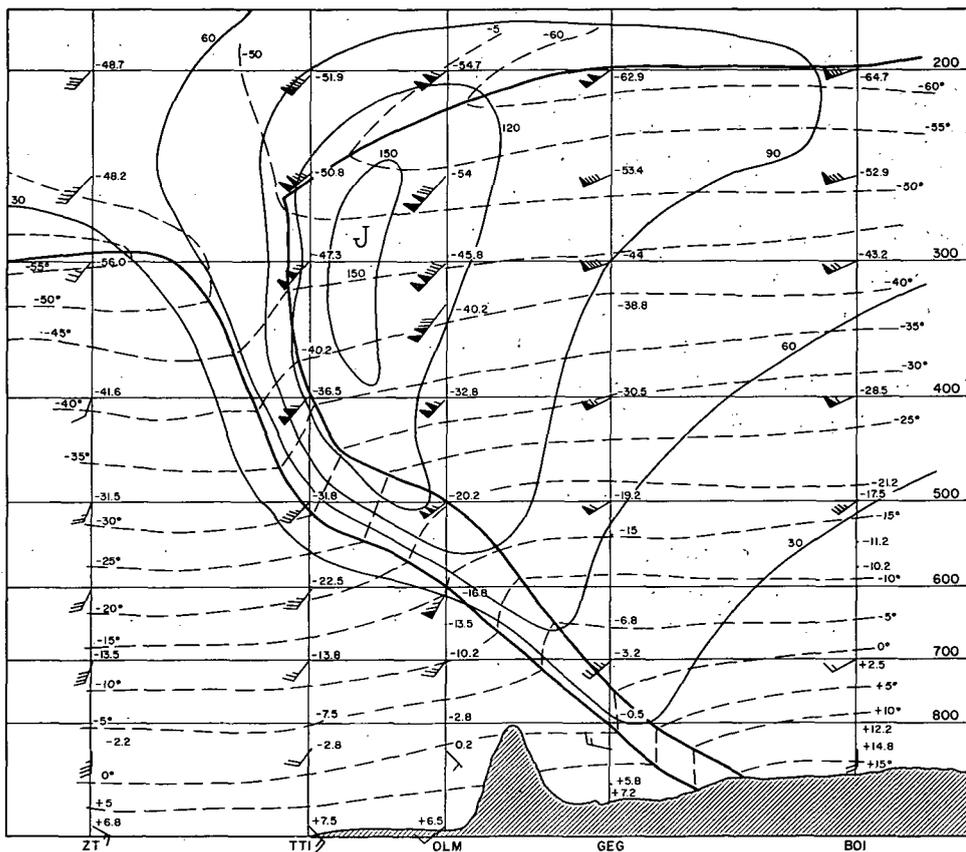


Figure 5
Jet Stream Cross Section Port Hardy to Boise For 6th May 1963, 1200 G. M. T.

so that flight 502 would experience the maximum possible tail wind component in the air stream. Conversely a flight bound from Edmonton to Vancouver over the same route would encounter the maximum head wind component.

4. HIGH-LEVEL TURBULENCE^X

The Nature of High-Level Turbulence

High-level turbulence is characterized by short random motions or accelerations of the aircraft which cannot be controlled by the pilot. These bumps are caused by eddies in the mean flow of the air stream, moving with the flow downstream. The eddies in the stream may range in diameter from inches to miles. However, the eddies affecting the aircraft will range from about 50 ft. to say 800 ft. in diameter. This represents only a small portion of the spectrum of existing eddies. However, those much smaller than 50 ft. will not produce significant bumps or motions in large aircraft. Those much larger than the upper limit result in a more sustained motion which may normally be controlled.

Relation of Eddy Size to Aircraft Response

The particular portion of the spectrum of eddy sizes which will affect a given aircraft depends among other things on the size and speed of the aircraft and its response to the gusts making up the eddies. Aircraft passengers feel the gusts that are large enough to accelerate the entire aircraft. Smaller gusts affecting only the control surfaces, may cause yawing or pitching of the aircraft or vibration of the responsive parts of the aircraft structure. The greater the size of an aircraft, the greater will be the optimum size of the eddy or gust required to produce an acceleration. Similarly at the other end of the scale, the larger aircraft will require larger sizes of the smaller eddies to produce a simple vibration.

^X In this report, turbulence is used in the sense of aircraft response, rather than in the meteorological sense which defines turbulence as atmospheric motions smaller than the mean flow.

The Relation of Aircraft Speed to Aircraft Response

The response function of each aircraft also varies with the speed of the aircraft in passing through the eddy. The greater the speed of the aircraft in flying through an eddy the sharper will be the response to the acceleration. The severity of turbulence may be eased by reducing the airspeed and this has been a recommended procedure.

The development of modern high-speed aircraft has led to unexpected problems in the field of turbulence. As aircraft sizes increase, so do the sizes of eddies increase which will produce accelerations or vibrations. As the speed increases, so does the severity of the turbulence increase. Eddies which produced relatively gentle motions of ascent or subsidence in smaller aircraft now produce unmanageable accelerations. Thus, greater size and speed only compound the problem of turbulence. With supersonic aircraft, response to eddies or waves of the order of a mile in diameter will result in accelerations which may be severe.

Drafts Associated with Standing or Mountain Waves

A larger scale of motion is found in the drafts or vertical currents associated with thunderstorms and mountain waves. These drafts may range in size from 2,500 to 25,000 ft. This means that the aircraft would respond to control while in the draft and the pilot may take corrective action. Entrance to the draft area may be accompanied by a sharp acceleration followed by smooth flight in either ascending or descending air. Note that drafts in cumulonimbus move with the mean flow, whereas standing waves as the name implies, remain stationary with respect to the terrain causing the wave.

This means that speed of entry into the draft is greater for an aircraft moving downwind into a wave than for the same aircraft flying downwind into a thunderstorm draft. A sharper acceleration will be experienced in the wave draft entry because of this greater velocity. Pilots are more accustomed to eddies imbedded in the flow and travelling with it, than they are to the stationary wave structures.

The areal size of the downdraft or updraft in a mountain wave is determined by the wavelength. This in turn is a function of the mean wind speed in the air stream flowing over the mountain, and the stability of the airstream. In general, the wavelength varies directly with the airspeed. Lengths of 2 to 20 miles are common in tropospheric waves.

It should be noted that flow in the intermediate levels of a standing wave is usually exceptionally smooth. Some pilots identify wave flying by the smoothness of flight. This characteristic is not true at levels near the tropopause where clear air turbulence is usually found, nor at the mountain top level where rotors beneath the wave crests cause violent turbulence.

Vertical velocities in the standing waves in the lee of the Rockies have been found to reach 5,000 ft. per minute and more. The waves are not necessarily symmetrical and downdrafts may be stronger than updrafts. Control measures may be inadequate in these cases since aircraft control measures cannot compensate for velocities of such magnitude. Indeed they should not be attempted since they will make the transition from one draft to its reciprocal more difficult.

5. THE METEOROLOGY OF MOUNTAIN WAVES

Necessary Conditions

The meteorological conditions for the formation of a standing or mountain wave, are well established. The conditions include:

i) A wind flow which increases steadily with height to near the tropopause, and which has a minimum velocity of 20 to 25 kt. at mountain-top level. The stronger the flow in this zone, the greater will be the effect.

ii) The wind direction must be fairly constant with height and should be nearly at right angles to the ridge. In practice it is found that the direction may be 30° to either side of perpendicularity.

iii) A stable layer in the airstream, near the mountain top level. This is usually topped by a less stable or even unstable layer. There may be an unstable layer at lower levels.

Scorer has shown that a necessary condition for wave formation is that the Scorer number 1^2 should decrease with altitude. This number is a complex term involving the stability and the mean velocity of the air stream.

Wavelength of Mountain Waves

The wavelength also depends on the Scorer number and is equal to $2\pi/l$. Since l varies inversely with the wind velocity and directly as the square root of the stability term, the velocity is the determining factor in the wavelength of a standing wave. It is quite possible and usual for a stream to have different natural wavelengths in different layers of the air stream. There may be a much longer wavelength near the tropopause than at a lower level. These different wavelengths interact in a complex manner, sometimes reinforcing or cancelling each other.

Amplitude of Mountain Waves

It is found that the amplitude of the wave varies with shape of the mountain profile or obstacle as well as with the stability of the airstream. If the size and shape of the mountain profile coincides with the wavelength of the airstream then the amplitude of the wave will increase. It is possible for a ridge or ridges downstream from the main range to cause a resonant effect which also magnifies the amplitude. This occurs when the ridge is one wavelength or a simple multiple of the wavelength, downstream from the range.

The amplitude is also critically dependent on the airstream characteristics. One theoretical result is that larger amplitude waves may be expected from an airstream with a shallow layer of marked stability, than from a deeper layer of less stability. The greatest amplitude occurs in the stable layer and decreases both above and below the stable layer.

Because of the complexity of the factors affecting amplitude it is not possible to state what the amplitude should be under any given set of circumstances. It is noted that amplitudes (depth from crest to trough) of 7,000 ft. have been measured in strong standing waves.

6. APPLICATION OF NECESSARY CONDITIONS TO MAY 6th, 1963

A study of the upper air charts and tephigrams reveals that the necessary conditions outlined in paragraph 5 were exceedingly well met on May 6th. It may be stated with reasonable certainty that a system of standing waves existed downstream (to the northeast) from the Divide.

A composite tephigram (Fig. 6) was constructed for the region of the reported turbulence. This was used to compute the Scorer number for layers of 50-mb thickness in Table I.

TABLE I
VALUES OF SCORER NO. l^2

50-mb layer below	$g\beta$	U	l^2	Wavelength $\lambda = 2\pi/l$
300	1600	130	0.11	19
350	1300	110	0.10	20
400	1300	105	0.11	19
450	1100	105	0.10	20
500	3100	92	0.36	10
550	3100	75	0.55	8.3
600	1900	58	0.57	8.3
650	1400	38	1.0	6.3
700	1400	25	2.2	4.2
750	1400	10	1.4	--

It is seen that l^2 decreases markedly with height. In the very stable layer from 600 to 500 mb the wavelength is close to 8 miles. There is a different wavelength in the upper troposphere of near 20 miles.

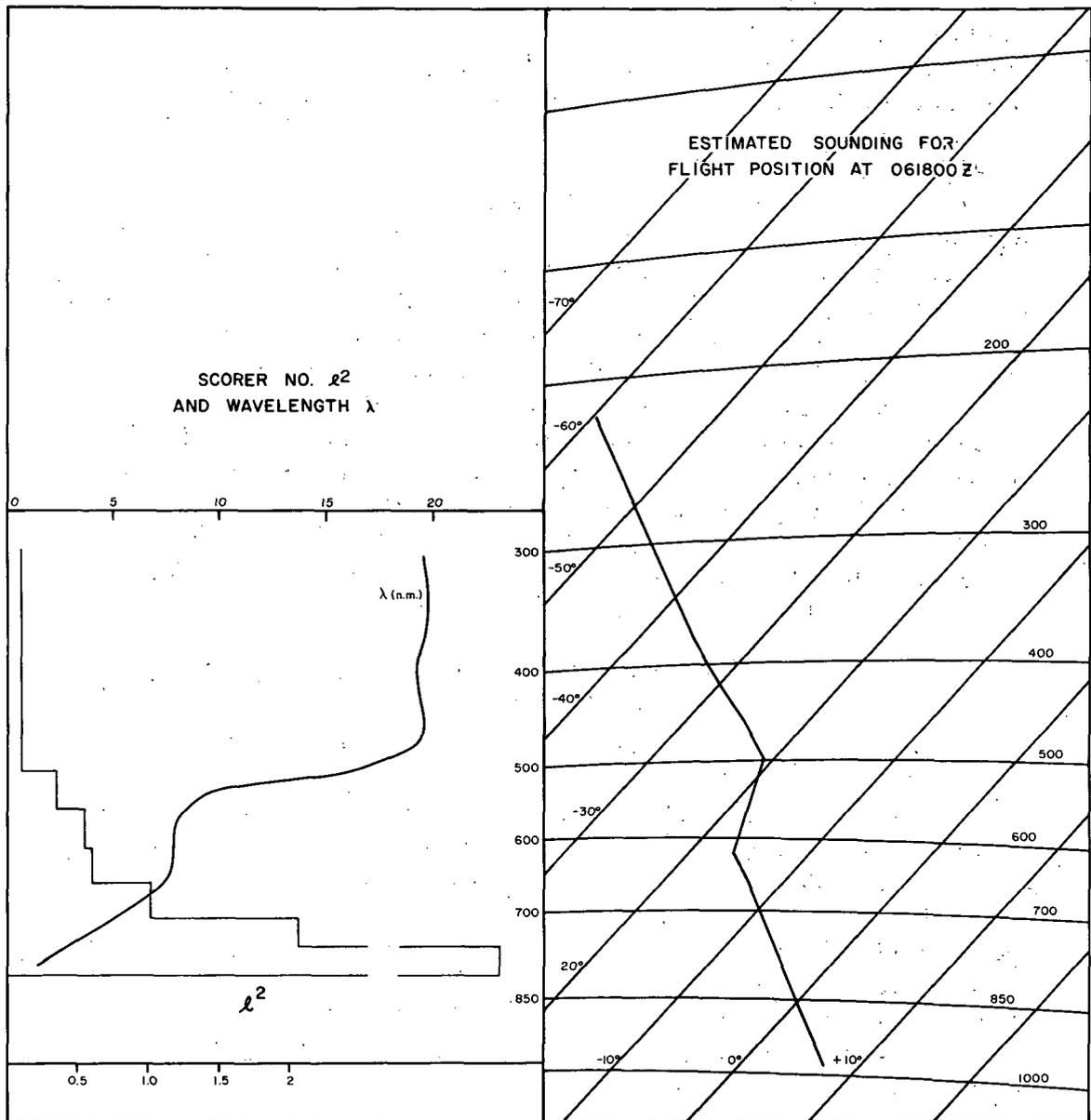


Figure 6

The wind profile was nearly constant in direction and velocity increased steadily with height.

It will be remembered that Fig. 1 showed that terrain features were spaced regularly about 6 to 7 miles apart downstream from the Divide. The size and shape of the ridges is then very similar to the wavelength in the stable layer. If the 2nd and 3rd ridges downstream are treated as one composite mountain (which is the way an airstream often acts), then the terrain features would exhibit the 1st ridge 6 miles downstream, the second, 8 miles further, and the third ridge 8 miles still further downstream.

This is then a very favorable situation for the development of a wave of maximum amplitude and of maximum vertical velocities. It can be stated that the wave had a length of close to 8 miles, that the amplitude increased with each resonant ridge downstream from the Divide, and that the vertical velocity likely increased from one wave to the next. These conditions would prevail for the first four waves with the waves weakening downstream from that point. Actual values for the amplitude and vertical velocity cannot be determined easily. However, from previous occurrences in the Rockies, it may safely be said that the amplitude in the third or fourth wave would reach 7,000 ft. and the vertical velocity at least 5,000 ft. per min. Fig. 7 suggests a possible reconstruction.

7. RECONSTRUCTION OF FLIGHT EXPERIENCE

Explanation of Reported Sequence of Events

It appears from all evidence that Flight 502 encountered a standing wave of increasing severity while crossing the Divide. The first waves of small amplitude warned the pilot of a change in flight conditions so that he began to reduce power and ordered seat belts fastened. The succeeding waves of greatly increased amplitude and vertical velocity produced the severe jolt in which the plane dropped 800 ft. in 3-5 seconds; a choppy interval (updraft zone); followed by a second downdraft or jolt.

Wave Amplitude and Vertical Velocity

This is an entirely reasonable hypothesis since the amplitude of a wave may double from one wave to the next

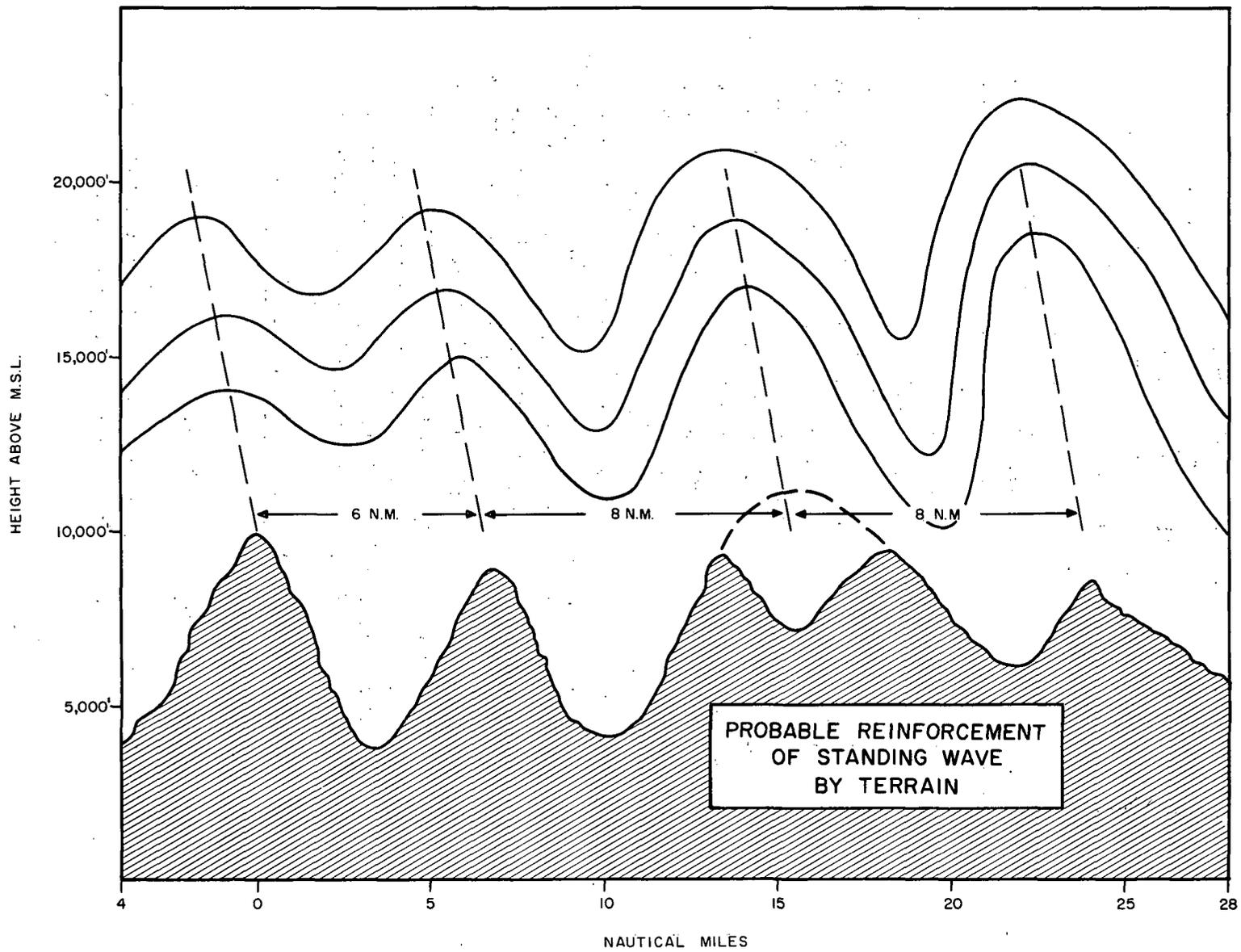


Figure 7

when a resonant ground feature is correctly situated to reinforce the wave. It is also noteworthy that the flight path is at right angles to the wave train, so that the plane passed through each wave in the shortest possible distance. The vertical velocity suggested by a drop of 800 ft. in 3-5 seconds is staggering. This would be at least 10,000 ft. per minute, a magnitude which has seldom been measured in either mountain waves or thunderstorm drafts. However, under the circumstances the estimate should be treated with some caution. The time estimate was subjective at best and was made under conditions of extreme stress.

It might be stated that the vertical velocity was somewhere between 5,000 and 10,000 ft. per minute but no firmer estimate can be reached.

Estimate of Wavelength

With regard to the wavelength it is noted that the period of sharp descent would represent approximately one-quarter wavelength. Remembering that the aircraft takes some time to respond to the acceleration and that the time estimation of 3-5 seconds is subjective, it is quite possible that the one-quarter wavelength is two to three times as long as the five seconds would represent. Taking a figure of twice five seconds for the quarter wavelength, the plane would fly through a complete wave in about 40 seconds. An estimate of the Vanguard's true airspeed at the time of the jolt would place it between 360 kt. and 320 kt. (recommended speed for turbulent air). Taking a speed of 341 kt. and the tail component of +151 kt, the aircraft would have a ground speed of 492 kt or 5.5 nm in 40 seconds. Using three times the five second figure for a quarter wavelength would have the plane fly through a wave in 60 seconds -- in which time the plane would have covered eight nautical miles. This is in good agreement with the wavelength calculated from theoretical considerations.

8. EXPERIENCE OF OTHER FLIGHTS ON MAY 6th

Available Flight Reports

Other aircraft flew over this route or adjacent routes on this day. Why did no one else report such a severe

jolt? The meso-structure of the jet stream is difficult to picture exactly and conditions vary greatly over short distances. A wave only eight miles in length is also a very fine or meso scale structure and certainly varies within our coarse network of observations. However, a total of 13 pilot reports was available for flights over the Rockies in the 26 hour period from 060100Z to 070300Z. Some deductions may be made from these reports.

Flight 503-6

The closest observation to the time of the incident under investigation was from Flight 503. This was also a Vanguard flying over the same route only 2 to 3 hours earlier than #502 and at practically the same Altitude. 503 reported turbulence at 20,000 ft. out of Edmonton and changed to 22,000 ft. where occasional moderate turbulence and strong subsidence were reported. Because of the preliminary turbulence, 502 had reduced cruising speed to 320 kt. The significant difference between the two flights lay in the fact that they flew in opposite directions. 503 was approaching the jet maximum and so reported a wind of only 112 kt. However, this was a headwind and so reduced ground speed to 208 kt. This means that 503 entered the wave structure at a very much slower speed than did 502. It would take 503 at least two minutes and 20 seconds to fly through a wave of 8 nm, whereas 502 would accomplish this in 60 seconds. This is due to the fact that the draft in the standing wave is stationary with respect to the terrain.

Alternative Routes

The 13 pilots reports may be divided into three divisions covering the three routes Edmonton to Vancouver, and Lethbridge to Vancouver. All routes cross the Divide at different latitudes.

The Southern Route

Two flights were made over the southern route from Lethbridge to Vancouver. Both were DC-8 equipment and flew at 31,000 ft. Neither flight reported any subsidence or turbulence at flight levels.

The Intermediate Route

There were five flights on the route from Calgary to Vancouver. One DC-8 flew at 31,000 ft. and reported no turbulence or subsidence. Two Vanguard flights at 18,000 and 19,000 ft. respectively both changed cruising altitudes because of turbulence but failed to get out of the turbulent air. A Viscount (travelling westbound against the wind and of course at a slower speed than either the DC-8s or Vanguards) flew at 20,000 and 22,000 ft. and encountered light turbulence and chop at all altitudes. A Convair (CPA 3-5) at 16,000 ft. found subsidence over the Divide between Calgary and Kimberley.

The Northern Route

Six flights were made on the northern route from Edmonton to Vancouver, two of which have been noted. Three flights were DC-8 equipment. The first at 32,000 ft. eastbound 12 hrs. before Flight 502 reported light to moderate turbulence over the entire route as well as on ascent and descent between 20,000 and 32,000 ft. The second, also about 12 hours prior to 502, was westbound and reported no turbulence at flight level of 31,000 ft. although he indicated light to moderate turbulence from 15,000 to 26,000 ft. on climbout of Edmonton. The third, also westbound, reported no turbulence at 35,000 ft. except over the extreme western leg. The sixth flight was a Viscount at 25,000 ft. and reported turbulence over the Divide, a smooth period, and further turbulence on descent at Edmonton.

9. MERITS OF ALTERNATE ROUTES

All flights on the Edmonton - Vancouver route reported turbulence and/or subsidence except two of the high-level flights, both of which were westbound.

On the Calgary-Vancouver route all flights between 16,000 and 25,000 ft. reported turbulence and/or subsidence, but this was not experienced at 31,000 ft.

On the Lethbridge-Vancouver route no subsidence or turbulence was reported at high levels. In view of the Calgary route reports, it must be stated that turbulence and/or subsidence were likely present to some extent at intermediate levels over this route near the Divide.

10.

CONCLUSIONS

1. It is a reasonable hypothesis to state that Flight 502-6 sustained two damaging jolts when entering the down-drafts of a series of standing waves in the lee of the Divide.

2. The severity of the jolts was occasioned by the rapidity with which 502 entered the standing wave downdraft.

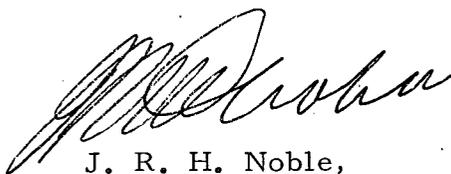
3. In such a situation, reducing the airspeed of the eastbound aircraft would not produce a sufficient decrease in ground speed to avoid damaging accelerations.

4. Slower flying aircraft would not likely sustain such severe accelerations, even when flying east.

5. Aircraft flying west, even with the same air-speed as 502, would not likely experience any severe accelerations.

6. Dogmatic statements should not be made about the merits of the routes through Calgary and Lethbridge when the northern route is experiencing standing wave conditions. However, the terrain features in the lee of the Divide on these routes do not show a succession of ridges. From this, it might be concluded that a situation such as 502 encountered would not occur on the southern routes.

APPROVED,



J. R. H. Noble,
Director,
Meteorological Branch.

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Department of Transport - Meteorological Branch

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17 pps. 7 figs. 1 table.

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