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Geological Survey of Canada

A STUDY INTO THE FEASIBILITY OF MEASURING GRAVITY FROM AIRSHIPS

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A STUDY INTO THE FEASIBILITY OF MEASURING GRAVITY FROM AIRSHIPS

Part 1

Principal Investigator's Report

Part 2

Statement of Requirements for the Study

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A STUDY INTO THE FEASIBILITY OF MEASURING GRAVITY FROM AIRSHIIPS.

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Introduction.

Canada has established a Regional Gravity net which covers much of the country. The net is based on a 5 km. grid, and the gravity measurements are believed to be accurate to within 1 or 2 mgals. R.M.S. error. Much of the net has been established by measurements using standard land gravimeters, and it is considered that the errors in these measurements arise mainly from uncertainties in the elevation of the stations and in the topographic corrections to the basic measurements. Some of the net was established using marine gravimeters on a ship, and the errors in these measurements arise largely from the uncertainties in the corrections which have to be applied to the basic instrumental reading.

There are substantial areas of Canada which cannot be easily surveyed using either land or ship gravity technology. Foxe Basin is too shallow for the safe operation of the large ships which would be needed for gravity surveys in the area, and it does not freeze over sufficiently to allow land gravimeters to be used on the ice. This is only one example of many areas in the arctic for which there is no easy means of collecting gravity data. The mountainous parts of British Columbia and the Yukon are also difficult to survey using conventional meters and transport. There would appear to be considerable potential for gravity surveys from aircraft in these regions, especially from airships, which can fly more slowly than aircraft. This report presents the information gathered from published and unpublished documents, and also from experts in the field, which should assist those concerned to decide whether or not to embark on a Canadian airborne gravity program.

The Basic Theoretical Requirements for Airborne Gravity Measurements

The basic requirements are described in the report by Bower and Halpenny, which gives a very good overview of the whole field of airborne gravimetry. The technology is based upon that used to measure gravity at sea, but with the additional complications of the need to measure the vehicular position and motions in the vertical axis. In addition, since the horizontal velocity of an aircraft is greater than that of a ship, the corrections to the raw gravity measurements are greater.

The vertical free air gradient of gravity is 0.31 mGal. per metre, so the altitude of the measuring platform must be known with an accuracy of approximately 3 metres in order to reduce the measured value of gravity to the value which it would be at the geoid. The mass of the ground above the geoid must be determined, which involves knowing the altitude of the ground underneath the measuring platform. This correction demands a comparable accuracy, but also requires that the altitude of the land should be known for a distance around the point of measurement.

The horizontal gradient of gravity is less than 1% of the vertical gradient, so the positioning accuracy is correspondingly less.

A vertical velocity of the platform has no inherent effect on the gravimeter, except insofar as the altitude is changed. But a variation in the vertical velocity gives rise to a vertical acceleration which cannot be distinguished from a change in the gravity field. The gravimeter itself is very heavily damped, and in addition the output signal is filtered, usually with several filters which attenuate any component having a periodicity of less than about 20 seconds. Finally the data analysis process includes another filter with a period of 60 seconds or more. If the platform oscillates vertically with a periodicity of 60 secs., an amplitude of 1 cm. will correspond to a velocity of 0.1 cm./sec. and an acceleration of 0.01 cm./sec./sec. or 10 mGals. If the period of oscillation is longer than 60 secs., the velocity and accelerations are reduced, of course. Clearly, this poses a very stringent demand on the measurement of the vertical velocity or of the vertical position, from which the vertical velocity can be derived.

The horizontal velocity of the gravimeter platform gives rise to an acceleration known as the Coriolis acceleration, and the vertical component of this acceleration is known as the Eotvos effect. The effect varies with latitude and direction of motion, being highest when moving East - West at the equator; at the latitude of southern Canada, an East - West velocity of 0.1 metre/sec. gives rise to a correction of 1 mGal. The velocity is averaged over the period of the gravimeter filter, and so requires a position accuracy of 4 metres.

A marine gravimeter is designed to have no response to horizontal accelerations, but this can only be true if the meter is maintained in a fixed vertical position. This can theoretically be achieved by mounting it on a gyro-stabilised platform with a natural period of 84 minutes (the period of a pendulum whose bob is at the centre of the earth). In practice, a gyro-stabilised platform is used to stabilise the gravimeter, but the natural period is much less than 84 minutes, since the 84 minute platform in practice suffers from serious perturbations due to system imperfections. If the aircraft is laterally displaced, the shorter period gyro-stabilised platform will tilt slightly; this can affect the gravimeter reading, a tilt of 4 minutes of arc giving an error of 1 mGal. In addition, if a horizontal acceleration is experienced while the platform is off-level, the component of the acceleration which is along the axis of the gravimeter will cause an error. If the platform is tilted by 4 minutes of arc, a horizontal acceleration of 0.8 cms/sec. in the same direction as the platform is tilted will cause an error of 1 mGal. Such a horizontal acceleration could be caused by the aircraft flying at a velocity of 40 knots along a circular track with a radius of 40 km. Measuring such a track requires a horizontal positioning accuracy of 3 metres.

The corrections for horizontal accelerations described above apply to all gravimeters. In addition, many meters have a design such that the meter is sensitive to horizontal accelerations if the beam is not levelled - i.e. the meter is not at its zero reading. This correction is usually calculated in real-time using a dedicated computer, which may also be used to calculate the correction arising from the platform tilt. It must be noted, however, that detecting when the gyro-platform is off-level is not easy.

In order to measure gravity from an unstable platform such as a ship or an aircraft, the gravimeter must be specially built with very heavy damping and electronic filtering in the output signal. There are two manufacturers of suitable meters - LaCoste and Romberg in the U.S.A. and Bodenseewerke in Germany; Bell Aerospace in the U.S.A. also makes a meter, but it has not achieved extensive popularity. The Lacoste Romberg meter, which is the most widely used sea gravimeter, has three cascaded output filters each with a time constant of 20 seconds. The predominant motions of a ship originate with the natural wave period (which may range from 6 to 20 seconds), and the ship's roll and pitch periods (which are usually less than 30 seconds). The amplitude of the motions of a plane may be thought to be usually less than those of a ship, but a small plane flying close to the ground is subject to much more vigorous motions than a large jet flying at high altitude. Ships operate in a wave environment which is relatively regular, but the atmospheric disturbances in which a plane operates are much more random in nature – with components covering a very broad range of frequencies. It is therefore not necessarily true that the standard marine gravimeter has the ideal characteristics for measuring gravity from the air, and it would seem likely that output filters with variable time-constants should be used.

The gravimeter must be mounted on a high quality gyro stabilised platform. The platform will be fitted with accelerometers to measure the instantaneous horizontal acceleration experienced at the platform, from which the levelling force is derived. The outputs from these accelerometers may be suitable sensors for the horizontal acceleration corrections which must be applied to the gravimeter, but if they are not then extra accelerometers must be mounted on the platform.

The data from the gravimeter, the accelerometers, the platform, and the navigational system must either be recorded for subsequent data analysis or a computer must be carried to carry out the analysis in real time. It is probable that a combination of the two will be the best solution, with some analysis carried out on board and some after the survey has been completed.

Navigation of the Aircraft.

The precise navigation of the aircraft is the key to the success of airborne gravity surveying.

For surveys of limited extent, radionavigation systems which measure the range from the aircraft to three or more ground stations can give the accuracy needed for horizontal positioning, calculation of the Eotvos correction, and calculation of cross-coupling corrections. Such systems require land bases, and are not capable of giving the required accuracy over ranges of several hundred kilometres. They give no indication of altitude, so that a completely independent altitude system is required.

The Global Positioning System, or GPS, satellite navigation system can meet the horizontal positioning accuracy requirements anywhere in the world when used in the dual frequency, differential, mode. It would appear that it can achieve the required accuracy using reference receivers located several hundreds of kilometers from the active receiver. But the system is not fully operational at the present time, since the full set of satellites has not yet been placed in orbit. As a result, positioning can only be achieved for a few hours each day. It will probably be 1990 or 1991 before the system is completely functional, and even then there may well be a snag.

The GPS has been designed and installed for military purposes. At present, accurate information on the satellites' orbits is freely available to any user; the data is not quite as good as had been projected when the system was originally announced, but it is still fully adequate for the purposes considered above. But it has been clearly stated that as soon as the system is fully operational, the orbital data made available to non-military users will be degraded very substantially - by something like an order of magnitude. It was recently stated that the degradation would probably be started after the next satellite was put into orbit, although this is not certain. There has been no indication as to how the data might be degraded, although there has been some indication that fully accurate orbit data might be made available with a time delay of a few days. The military are well aware that differential GPS can be used to improve the accuracy of the system, and it can be expected that when they select the method of data degradation, they will ensure that the differential method of operation will be affected at least as much as the normal system; and there can be no guarantee that the delayed data will enable the full potential accuracy to be achieved even after the few days delay.

The uncertainty about the GPS does not mean that it should not be considered as a viable method of navigation, but there is at present just no knowledge of what its capabilities will be in the future; without differential GPS, wide-ranging accurate airborne gravity measurements would not seem to be feasible since the Eotvos corrections could not be calculated with sufficient accuracy.

The measurement of vertical velocity of the aircraft, which is needed to calculate the vertical accelerations of the aircraft, is the major problem which has to be overcome in order to make accurate airborne gravity measurements. Those involved in the field have investigated four approaches to the problem.

The first is to use a specially built radar altimeter; this can be built from standard electronic units, and can have a resolution of 1 cm. or less, which should enable gravity measurements to be made to within 1 or 2 mGals. But it can only be used over water of known elevation, since the elevation measured over even precisely surveyed land can be affected by vegetation. In addition, the existing system uses a considerable amount of power and is very bulky and heavy; both of these problems could probably be overcome with some development work.

The second approach is to use a precision laser altimeter. A suitable device is available commercially, is not excessively heavy and has moderate power requirements. As with the radar altimeter, this can only be used over water. It has given good results at times, but there have been occasions when the light reflected from the water surface was not reflected to the aircraft, but to one side, so that no reading could be achieved. Low clouds or fog also prevent its use. In the opinion of those who have had practical experience with the equipment, its use for routine surveys is doubtful.

The third method uses the ambient air pressure as a measure of altitude. The aneroid barometer has been used for many decades to measure height, and the standard altimeter used in aircraft is basically an aneroid barometer. The rate of climb indicator is a differential barometer. But the accuracy required for gravity measurements is much greater than that achievable by commercial instruments. The main problem is to design and install a probe which can "sample" the ambient air pressure accurately even though the aircraft is moving rapidly through the air. The conventional approach is to mount a gimballed probe ahead of the aircraft, which aligns itself precisely with the air flow, and to sample the air pressure through small holes drilled in the side of the probe. An alternative approach, for a helicopter, is to mount the probe above the main rotor. It is remarkable that accurate data can be achieved using these probes at speeds of up to 400 km. per hour, but experimental data demonstrates the validity of the technology. Suitable sensors for measuring the pressure are available commercially.

The fourth approach is to use differential GPS. Theoretically, under ideal conditions, the vertical velocity can be measured sufficiently accurately to give corrections accurate to 1 mGal. if the instantaneous measurements are averaged over a one second period; measurements have been made using two fixed GPS receivers which show that the accuracy achieved in practice is an order of magnitude less than that. But the errors to which an airborne receiver will be subject are as yet unknown. Radio waves propogating through the atmosphere have a velocity which depends both on the density of the atmosphere and also on its water content. An aircraft flying on a course which places a cloud between the receiver and the satellite will indicate a spurious GPS reading - small, but potentially significant. In addition, the noise generated by electrical interference from auroral effects can degrade the signal very significantly; this effect will, of course, be most felt in the Arctic during periods of maximum sunspot activity. There have been very few observations made in the field, but the available evidence shows that these two sources of error could be sufficiently large that GPS alone cannot be relied upon to give consistently accurate data.

The Performance Achieved by Current Airborne Gravity Operations.

There are at present two groups which are actively involved in airborne gravity measurements, the U.S. Naval Research Laboratory and Carson Geoscience. Their operations are briefly described here, but much more information may be obtained from the references listed at the end of this report.

The operations of the U.S. NRL are directed by Dr. J. Brozena. He has been involved in airborne gravity measurements there for about five years, first developing the equipment and then using it on calibration and evaluation flights, as well as on airborne surveys. A P3 Orion aircraft is used, flying at a height of about 500 metres and at a speed of about 360 km. per hour. The aircraft is fitted with a specially developed radar altimeter, which is considered to be the most reliable source of altitude data, and also with a sensitive pressure altimeter. A standard Lacoste and Romberg model S gravimeter is used, mounted on its standard gyro-stabilised platform. The aircraft is fitted with a differential GPS navigation system, and also with a specially developed auto pilot system. Data from all these systems are processed with an on-board computer, and recorded on magnetic tape and disc, as well as being displayed in real time for the system operator.

Dr. Brozena has carried out a great number of test flights, mainly over the gravity range which has been established, using sea-bottom gravimeters, off the south east coast of the U.S.A. Published results of the tests indicate an RMS error of about 4 mGals., both with respect to cross-overs and also with respect to the ground measurements. He has also carried out tests over an area of Eastern N.

Carolina; this area is low lying country, with many large areas of water. For these tests, the radar altimeter was used when flying over water of known elevation, the air pressure altimeter being used at other times. The accuracies achieved on these tests were about 3 mGals. RMS. The filtered output from the Gravimeter was further smoothed by a digital filter, with a cut off of 200 secs. for the sea trials, and 100 secs. for the land flights. This resulted in spatial averaging of gravity over 20 km. and 10 km. respectively.

The flights on all tests were flown at night, since this was the time when the GPS satellites were above the horizon. It was noted in the reports that this also had the advantage that the winds and atmospheric turbulence are generally lighter at night than during the day. Surveys were made by flying a regular grid pattern, and it is inferred in the reports that each line was flown twice. Data processing was carried out on land, and involves extensive efforts. It is clear that the inspection of the raw data by an experienced operator can and does lead to the rejection of substantial amounts; and it is clear that the acceptable data is then subject to a great deal of adjustment to reduce cross-over discrepancies and fit the air data to any known surface data. Dr. Brozena lays great emphasis on the importance of the specially developed autopilot, and states that the gravity data is useless if it is not performing correctly. During discussions with Dr. Brozena, it was agreed that it was not clear what the sea reference level was for the radar altimeter - the (flat) troughs of the waves, the (first return) peaks, or something intermediate. The errors for the inland surveys, where waves are likely to be small, are appreciably less than those at sea, where waves are usually high; whether there is any link between the errors and the wave height is not known.

Dr. Brozena has successfully used a combination of radar altimeter and barometric altimeter when carrying out a survey over frozen sea. The radar was used over the flat ice, and the barometer when rafted ice was encountered. He has also made flights to compare the performance of pressure, radar, and laser altimeters, but has yet to analyze the data from these flights.

A comparison between GPS measurements and radar altimeter data was made in 1988. TI 4100 GPS receivers were used; these receivers have a single set of receiver electronics, and rapidly scan between the visible satellites. Four flights were used for the comparisons; good data was obtained on one of these, and data was obtained on another although the autopilot was not functioning properly. The results indicated very much better agreement between the two systems when the plane was under control of the autopilot than when it was flown manually, and it is difficult to explain this. But when the autopilot was operational, the elevations agreed satisfactorily if each was filtered through three sections of filter, each with a 40 sec. time constant.

The above comments indicate that many flights were made, during the total testing period, when useful data was not obtained. This should not be taken in any way negatively. The equipment used on these trials is complex, and is a unique assembly specially put together for this purpose. It is a prototype system, and as such has certainly been subject to modifications and improvements. This always results in a system which can give good results, but which is less reliable than a production system based upon the improved prototype.

Carson Helicopters have been involved in airborne gravity surveys for nearly 10 years, and have established an active commercial operation known as Carson Geoscience. The equipment was developed by Mr. W. Gummert, and has been used for many years to carry out surveys for oil exploration companies. The aim and the scale of the operations is substantially different than that of Brozena; fine horizontal resolution is required, over a relatively limited area, and it is probably fair to say that the oil companies are more interested in the delineation of gravity anomalies than that the gravity values should be extremely accurate. But for all that, Gummert claims to be able to measure to an accuracy as good as 1 mGal.

Carson Geoscience use a Lacoste Romberg model S gravimeter, and their initial work was done using a Sikorsky helicopter; they are also using a Norseman aircraft today, for surveys where the horizontal resolution is not critical. Positioning is achieved using either radio systems (such as miniranger) or GPS, and altitude by radar, laser, or barometric system.

Carson Geoscience are a commercial company, whose business is almost totally concerned with airborne geophysical surveys; they have seen the aeromagnetic survey business collapse as a result of an excessive number of firms attempting to break into the field, and do not wish to see the same thing happen in the aerogravity field. They have spent a considerable amount of money on developing their system, and wish to protect their investment. For both reasons, they are not willing to disclose details of their technology, except to their customers - it appears that the customers are allowed to participate in all aspects of the operation if they wish. Information is available from some sources, however (see the bibliography), and Bill Gummert was willing to talk about generalities.

They have carried out several ground-truth test surveys, including one over the S. Carolina test range, where they claim an R.M.S. error of less than 2 mGals., and another over a test range in Pennsylvania which was supervised by a consortium of ten oil companies. They have proposed to the U.S. Navy a survey over the Arctic ocean, but their offer has not yet been accepted. The cost of their surveys are in the order of $200 per km. for helicopter surveys, and maybe half that for aircraft surveys flown at 80 knots. In the latter case, experience shows that they can just barely achieve 5 km. horizontal resolution, which correlates with Brozena's results.

They developed the pressure sensor probe mounted axially above the helicopter rotor, which was described earlier in the report; they have also carried out extensive experiments to determine the best location for the sensor on the Norseman. They fly as low as possible, consistent with the terrain and safety considerations, and Gummert stressed that the special autopilot which they have developed is essential for both helicopter and Norseman. As with Brozena, Gummert says that manual control of the aircraft cannot produce any useful results.

They have patented the technology of airborne gravity surveying, in many countries including Canada, and the patent gives some indications of the technology they use. It indicates the necessity for keeping the gravimeter beam nulled at all times; and it notes that the normal Lacoste and Romberg filters are removed and 1.5 sec. filters substituted. The patent also indicates that much of the flying is done at night, when atmospheric conditions are good.

Gummert indicated that they fly a normal grid pattern survey, and also that they refly 25% to 50% of the lines. There is intensive data-selection based upon long experience and indicators from the raw data from the various measurements. This is followed by extensive data manipulation, using all available technologies and inputs; it was hinted that some of the technology may be derived from image analysis techniques. It appears that their system relies primarily on the barometric altimeter, particularly over the land areas which are their normal operating sites.

Based on the imformation outlined above, the following would seem to be a reasonable, perhaps even probable, guess at how Carson go about a survey.

The first step would be to carry out a quick aerial survey of the area to be flown, using aerial photography and other standard survey techniques to prepare a basic contoured map of the area. Using this, suitable sites for the ground stations for the radio positioning system would be selected. The ground stations would then be installed and carefully positioned, both for lateral position and for elevation; GPS would be the obvious method for this. The standard techniques would be used to verify that the navigation system is functioning correctly; at the same time, a standard land gravimeter would be used to make ground truth measurements at each ground station and possibly at other locations in the survey area where the helicopter can land without trouble. The grid would be laid out, and survey lines flown. Data from the first set of flights would be inspected for any obvious malfunctions, and then corrected using all the measured inputs, so as to obtain the first, basic, gravity map. Data from parts of the flight which were considered suspect would be marked. The network would be adjusted so as to minimise cross-over errors, using manual inputs and iterative recalculations to decide whether or not to reject the suspect data. Using this first adjustment, lines which require reflying would be identified. The lines would be reflown as required, and the data fed into the network in the same way as before. When the second or third adjusted net was produced, the whole would be adjusted using the ground truth gravity measurements. Finally, suspect areas could be checked using further flights, and possibly more ground truth gravity readings.

The above is pure guess-work, and must be treated as such. There is, however, a publication based on a survey carried out by Carson which contains some interesting factual data. The paper published in the Oil and Gas journal in 1987, describing a survey in the Moroccan Western Atlas Basin, gives two bouger gravity maps, one based on ground mesurements and the other on airborne measurements. There appear to be appreciable discrepancies between the two, especially around anomaly C ; Gummert said that this was due to the upward projection of the ground data, and he also pointed out that the land map was based on a single line across the South west corner. It would be most interesting to use the Earth Physics' Branch computer program to compare the two Bouger maps, in an effort to assess the actual accuracies achieved by the airborne survey.

When assessing the accuracy of any measurements, it must always be remembered that repeatability is not the same as accuracy. Thus, if a small hill in an otherwise flat terrain were to deflect horizontal wind in an upward direction, thereby causing a persistent pressure anomaly, a barometric altimeter would give a consistent error, which would be very repeatable and only detectable using some other independent method of measuring height.

Systematic errors can sometimes make data appear to be in error, and great care must be taken before any data is rejected. If there is a clear and certain reason to believe that the readings are incorrect (such as a failure of the gravimeter thermostat), then it is entirely rational to reject them. But readings should not be rejected merely because they do not agree with other readings. There have been occasions in the past when this was done, only to discover later that the 'good' readings were in fact the erroneous ones.

Both Brozena and Gummert are very insistent on the necessity for a very high quality autopilot. There seems no logical reason why this should be necessary, and this topic would seem to warrant investigation. The autopilot probably keeps the aircraft on a straight course, as well as minimising the porpoising of the aircraft; could the problems be associated with tilting of the gyro stabilised platform? The need for filtering the gravimeter output using long-period digital filters would seem to indicate that the corrections which are being applied to the raw gravimeter readings are not completely accurate, and investigations into this would also seem to be warranted.

Airships' Characteristics.

Airships have been operated since the beginning of the century. Zeppelins were used extensively during the first world war, and commercial passenger services were operated in the early thirties. The early airships used hydrogen to obtain lift, and the terminal disasters to the Hindenberg and the R 100 clearly showed that this was unacceptable. The availability of helium at reasonable cost, during the forties, sparked a renewed interest in airships. In particular, the Goodyear Rubber Company developed its Blimp, which has had a most successful history up to the present day; Goodyear have built more than 300 airships in their 60 years of activity, and the company has been active in developing new models recently. The blimps were used by the U.S. Navy to provide radar warning of approaching aircraft to naval ships, but the advent of missiles after the second world war reduced their popularity. The navy has no blimps at present, and there are only about a dozen operational units, mainly used for advertising purposes.

Until about ten years ago, Goodyear was the only manufacturer of airships with any continuing commercial success. There have been many new ventures in recent years, but most of the airships are too small to be considered as platforms for gravity measurements since they are only capable of lifting one or two people at most. The airships discussed here will be limited to those with a lifting capacity of 1,000 to 3,000 kilograms. The gravimeter itself, complete with its gyro stabilised platform, weighs about 250 kg., navigation, computing and data recording equipment will weigh another 250 kg., and a power supply for all the equipment will weigh 100 kg. Allowing for two operators and a pilot, it is clear that a 1,000 kg. payload is the absolute minimum, and for extended flights, which will require extra long range fuel tanks, 2,000 kg. is a more realistic minimum. A few airships with capabilities in excess of 3,000 kg. exist, but they are very bulky and would undoubtedly be expensive to operate.

There are four makes of airship which might be suitable for airborne gravity measurements - the Goodyear model G 22, the Airship Industries models Skyship 500 or 600, the US LTA model USA 100, and the American Blimp. The latter is too small for the existing gravimeter and equipment, but new and bigger models are being built which might be suitable for lighter, more refined gear developed in the future. It is not easy to be certain of the exact status of airship companies - the history of US LTA Inc. illustrates the problems. Their airship, the US LT-138S, started design as the US 100 in 1982, and was built by 1984. At that time, all the work was done by Grace Aircraft Corporation, of Eugene, Oregon. Grace aircraft became US Airship Corporation in 1985, and continued development of the US 100. In 1987 the assets of US Airship were purchased by Aerotek, Inc., but the company went into receivership in 1988 and its assets were purchased by US LTA Inc., which is currently reviewing the status of the airship program. A continuing airborne gravity survey program would obviously need to be certain that support for the airship would continue for at least several years into the future, and a series of changes such as the above would not give confidence in such continuing support.

Data on the potentially suitable airships are listed below.

The Goodyear G22 is 62.8 m. long and 14.6 m. in diameter. It has a volume of 7,040 cu. m., and can carry a useful load of 2,000 kg. Its maximum speed is 57 kts., or 104 km. per hour. It has a cabin about 7 m. long, 2.5 m. wide, and 2 m. high.

The Skyship 500 is 52 m. long and 14 m. in diameter. It has a volume of 5,140 cu. m., and can carry a useful load of 1,900 kg. Its maximum speed is 55 kts., or 100 km. per hour. It has a cabin 4.3 m. long, 2.2 m. wide, and 1.9 m. high. Its cruising range is 1,000 km.

The Skyship 600 is 59 m. long and 15.2 m. in diameter. It has a volume of 6,580 cu. m., and can carry a useful load of 2,900 kg. Its maximum speed is 60 kts., or 110 km. per hour. It has a cabin 6.9 m. long, 2.3 m. wide, and 1.9 m. high. Its cruising range is 1,000 km.

The USA 100 is 48.5 m. long and 12.8 m. in diameter. It has a volume of 3,900 cu. m., and can carry a useful load of about 1,200 kg. Its maximum speed is 50 kts., or 91 km. per hour. It has a cabin 4.1 m. long, 1.7 m. wide, and 1.9 m. high. Its cruising range is 600 km.

The American Blimp which is currently flying has a volume of 1,420 cu. m., and is only about a third of the size of the above airships; but new, larger, models are being built.

Despite the many years of history of airships, there is very little factual information published on their performance, especially in regard to accelerations experienced in flight. There are reports that the Hindenberg flew so smoothly that a coin, placed on edge on a table, would remain stable for some time. It is evident that most modern airships could not equal this; the records from an accelerometer on the Skyship 500 show around 10 Gals. vibrations from the engines and propellors - and only the Goodyear GZ 22 has a turboprop power unit, all others using conventional piston engines.

Gummert said that he believed that the French had made measurements of vertical movements of airships some years ago, and as a result had decided not to attempt to measure gravity from airships - but he had no details on this matter. He also claimed to have interviewed a thousand airship pilots, who reported that airships bound through the sky. He mentioned the relatively poor control of an airship, and believed that he had heard of a proposal to use aerofoils to control the airship, in a manner similar to that used to control a submarine. It is the view of the author of this report that his views may be a little overstated; for example, it is most unlikely that there are 1000 airship pilots alive today. It seems to be clear that flight in an airship can be very smooth indeed, when flying under ideal conditions of low winds and flat terrain, but that accelerations of up towards 1 g have been experienced when flying in mountainous terrain, with high and gusting winds. The accounts of flight testing the American Blimp in Arizona speak of "smooth flights" when flying during the "calm mornings", but as temperatures rise above 100 F. in the afternoon, of a "roller-coaster turbulence". They also recounted very high turbulence in a mountain pass when bucking a 60 m.p.h. head wind.

The broadly summarised general concensus of the few people contacted who have actually flown in modern airships is that they are not very different from a small plane, flying under the same conditions. Records of the Skyship 500 show vertical accelerations of about 10 or 20 Gals, when flying at speeds of 20 to 40 knots, and lateral accelerations of less than 5 Gals at 30 knots. These measurements are not definitive, or necessarily typical, since they are "background" to the accelerations experienced during manoeuvring tests of the airship. The data which are available are not sufficient to show whether the longer period accelerations which the airship experiences would be acceptable for airborne gravity, and it would seem that a special series of tests would be required to establish this. It should be noted that American Blimp are planning a series of instrumented flights in 1989, and have said that they would consider a request to release part of the test data to others with a specific use for the data.

The flight of an airship resembles that of a ship, in terms of response to the control surfaces. There is a noticeable delay between applying rudder and the reaction of the ship, and even then the ship "skids" sideways through the water for a time, rather than immediately taking up its new course. An airplane, in contrast, behaves in a way which is more similar to a car, with immediate response. As a result, an individual who is used to piloting an aircraft feels that the airship is wallowing through the air; and it is very probable that an autopilot which would control a plane would cause an airship to "hunt" about its intended course. The airship itself is critically damped in all except roll. There is no indication that any modern airship has ever had an autopilot fitted, so these comments are purely hypothetical.

Airships are usually inflated inside a hangar, and then towed out to a mooring mast. The mooring mast may be permanent (usually at the main base), mobile (i.e. mounted on a truck, but anchored with guy wires when in use), or transportable (i.e. taken to a site, assembled there and anchored with guy wires). Airships have successfully ridden out storms with 75 knot winds, moored to temporary masts. Indeed, a NASA - US Navy - DOT - FAA working group concluded that a mast could hold a ship of 1,500,000 cu. ft. safely in winds of up to 90 knots. So there would seem to be little concern regarding storm damage to an airship during summer months. It is claimed by airship enthusiasts that airships can fly when planes are grounded - but considering that the maximum speed of most airships is less than 60 knots, this statement may be a little biased. The airship would require a sizeable ground crew - more than that required to handle a small aircraft; figures quoted range from 6 to 12.

The U.S. Navy attempted to travel to the North Pole using a blimp. The expedition was not successful, having experienced severe damage to the airship as a result of icing problems. Brigadier-General Keith Greenaway is reported to be knowledgable about the expedition. It would appear that this had a major impact on Goodyear, who say that snow and ice "can crush an airship like an eggshell"; they also say that they will not consider operating one of their ships in the Arctic under any circumstances - Ontario during the summer is as far north as they will venture. Dr. deLaurier states that anti-icing sprays have been developed in recent years which are very effective.

Gummert said that he had considered that airships could be useful platforms to replace helicopters. He had looked into the feasibility some time ago. He said that he abandoned the investigations because he came to the conclusion that the ground handling problems which would be encountered in the isolated jungle areas which they normally fly, would be simply too great and too expensive. Airships routinely travel throughout the continental U.S.A. with no qualms. The conclusion to be drawn from this seems to be that it is necessary to ensure that any firm from whom an airship might be hired is willing to accept any possible risks of damage to the airship in the remote survey areas.

Airships today cannot be described as highly sophisticated devices. They have more in common with the DC3 aircraft than with the 737, but this comment is not intended to be in any way derogatory. An airship is inherently safe, in the same way as a ship or an automobile is safe - if any of the mechanisms break down, during a flight, the airship will not crash, but rather will stop. As a result, the extremely high standards of reliability which are necessary on a heavier than air craft are not needed on an airship, and less costly good quality commercial standards are sufficient. It must also be remembered that flying an aircraft demands continuous attention, whereas flying an airship is a much less demanding matter; an airship pilot can leave the controls for two or three minutes and go to make himself a cup of coffee, for example.

The airships which are currently flying fall into one of three categories; prototype airships, being used to develop a new design, recreational vehicles used to carry fare-paying passengers on sight seeing tours, or promotional and advertising vehicles. None of these categories demands very sophisticated services on board - although the recent introduction of airships carrying advertising messages which are internally illuminated at night, using many kilowatts of lighting, comes nearest to that classification. All airships claim a maximum height of 3,000 metres, although it is not clear what limits the height, apart from the unpressurized cabins. But most of the flying is done at low altitudes, seldom more than a few hundred metres, since the advertisers wish their messages to be seen, and the tourists want to see the world in close-up.

The airships are generally driven by relatively low powered gasoline engines. Airship Industries use Porsche engines, whereas other manufacturers generally use aircraft engines, such as Allison. The airships have the standard 28 v. aircraft electrical system, with alternators driven by the main engines generating about 1 kilowatt of power. Cabin pressure is not controlled, and the cabin is usually heated by air passing over the main engine exhaust system. Navigation is usually visual - the standard for small aeroplanes - although there is a growing tendency to move towards the technology which is expected today in small twin-engined piston planes, with radionavigation aids, blind flying instruments, etc.

The above may give the impression of a lack of precision. But each airship is outfitted to carry out the work which is demanded of it. An advertising blimp will not take off unless the skies are clear, because low overcast skies would prevent the populace on the ground from seeing the advertising message. Accordingly, visual navigation using standard maps, following main highways and railway lines from one town to the next, is an effective and foolproof technique. The rules which Government impose on the airship are relatively simple, although they are becoming more stringent year by year. But since the airship is so inherently simple and safe, there is no need for very demanding rules and regulations.

Any airship which is to be used for airborne gravity surveying will have to be treated rather like a very unsophisticated charter ship, and have instruments, power supplies, etc. fitted as required. Fitting the majority of the equipment will pose no problems, since the cabins are generally quite roomy, although the power units may be a little more difficult to mount in a location where they are reasonably quiet, but accessible for maintenance if needed. But it must be remembered that most of the structure of the airship is flexible, and mounting antennae etc. may require unorthodox approaches. It is unlikely that they could be satisfactorily mounted on the top of the airship; but since the airship body is a gas-filled bag of fabric, there would seem to be no reason why the antennae should not be mounted on top of the cabin, inside the main envelope. One of the biggest problems may be the vibration from the main engines, both in the effects on the equipment and also on the operators. The development of airships with turboprop power systems should be watched with interest.

It should be noted that Goodyear were the target of a hostile take-over attempt in 1986. They survived the attempt, but divested themselves of their aerospace plant in the process. The new company is Loral Systems Group; they are not making airships, but are supplying parts for the existing craft. Goodyear continue to operate their fleet at the present time.

There are more Skyships flying than airships of any other make, and either of the models could be used for gravity surveying. The future of the USA 100 is uncertain; the American Blimp is too small; and an airship built in Germany, the WDL 1, which might conceivably have been suitable has been sold to Airship Industries.

The conclusion from the above is that there is only one realistic source of a suitable airship today - Airship Industries. The flight characteristics are unknown, and testing would be required before any extensive operations are planned. But the available models are certainly capable of carrying the equipment needed for air gravity surveys, with a reserve for other equipment. Although they do not have the history of Goodyear, Airship Industries have excellent technical capabilities. The U.S. Navy has recently awarded a major contract to them, in association with Westinghouse. The contract is to design and build a prototype airship fitted with high-performance radar capable of detecting surface-skimming missiles, and it is planned to equip each U.S. fleet with one of these airships. The tender was won against competition from Goodyear, even though the price of the winning tender was higher than the other. It is very clear that the U.S. Navy believes that the technical competence of Airship Industries is of a very high order, sufficiently so to overcome the disadvantage of it being a foreign manufacturer.

The Performance of GPS.

The GPS system, using the satellites which are presently in orbit, allows positions to be determined over a period of several hours each day. There has been extensive testing of GPS in its normal mode since the system was initiated, but relatively little testing in the differential mode. This summary will only consider operations in the differential mode, since that is the only way to obtain the accuracy required for airborne gravity measurements.

When discussing GPS operations, great care must be taken to differentiate between experimental observations and theoretical predictions; the two are frequently intermingled. The University of Hamburg, for example, stated that Germany had a GPS system which would give navigational data sufficiently accurate to permit gravity measurements to be corrected to better than 1 mGal. Further discussion revealed that what was meant was that they have computer programs which are designed to compute navigational data to that accuracy; but that they have not yet tested it experimentally.

Differential GPS has, for the most part, been tested using two fixed stations, and, using one of them as the reference, measuring the apparent movement of the other. This is not the same as comparing a mobile station with a fixed station - one obvious difference is that multipath effects are likely to have a completely different impact with a mobile antenna, as compared to a fixed one. Nevertheless, there seems to be no reason to suppose that the design of equipment, measuring techniques, and correction algorithms should not be sufficient to effectively eliminate such differences as operating experience is obtained. But there are two problems which may not be easy to overcome. The first concerns the effect of the atmosphere between the satellite and the receivers, the second the effect of electrical noise interference.

The velocity of propagation of radio waves in the atmosphere depends both on the density (air pressure) of the atmosphere between the satellite and the receiver, and also on its moisture content. Both factors vary with time and position, but the variations are generally not very rapid. If one of the receivers is moving through the atmosphere, the variations could conceivably be sufficiently large and rapid as to cause navigational errors which would give rise to unacceptably large errors in gravity. Such errors have not been observed, and might be very rare - but the point should be thoroughly tested before gravity surveys are undertaken. The effect of electrical noise and localised ionospheric perturbations on the received signal is that the measured position is subject to a jitter, with a total magnitude of up to 1 metre and with rapid variations of several decimetres. Smoothing the navigational data should result in a reduction of the jitter, and in low latitudes the experimental observations indicate that such smoothing can give fully acceptable results. But in the northern parts of Canada, and at times of high sunspot activity, it is not clear that the averaging periods required to reduce the jitter to acceptable levels will not be so long that airborne gravity measurements are effectively ruled out. Atmospheric (tropospheric) effects are of the order of 5 metres in total, and although the use of tropospheric models can reduce this, the residual will be 5 to 8% of the total, and there are likely to be differences between the paths to the two receivers.

It was noted above that experiments have been carried out in moderate latitudes using two ground stations. The experimental data indicates that the errors and noise experienced are sufficiently low to allow GPS to be used as the navigational system for airborne gravity (Kleusberg, 1988). A comparison has been made by Brozena et al. between vertical velocity as measured by GPS and radar altimeter. The results are perplexing. The difference between the two systems varies dramatically, depending on the control of the aircraft. When flown using manual controls, making gentle turns, the differences are about four times greater than when flown manually on a straight course; and flying using the special autopilot reduces the differences by a further factor of three. The discrepancies could be due to either system, and it might be thought that the radar altimeter could perhaps be suspect, since results from gravity surveys using it are only consistent when the autopilot is used. But there is no obvious reason why either system should be affected by the way in which the aircraft is flown, and clarification and explanation of the differences should be made before any gravity surveys are undertaken using either system.

It is easy to demand a comparison between the two systems, but much less easy to design an appropriate experiment to achieve the desired results. A third, precise and reliable, system is needed, and the only candidate appears to be the laser altimeter.

A lake, newly frozen so that no ice ridging or rafting could have occurred, and preferably coated with a dusting of snow, would provide a suitable test surface. Seiche detectors should be installed round the shores, to detect any oscillations within the lake, but it should not be difficult to ensure that the surface is level to an accuracy of a few millimetres. Commercial laser altimeters are available which can measure elevations to within millimetres, and consequently the reference altitude obtained will be more precise than is needed for airborne gravity measurements. The test flights should carry a GPS system, a radar altimeter, and a pressure altimeter so as to enable each system to be tested. Even then, the results may not be conclusive, since conditions would be ideal for both the pressure and the radar altimeters, and they might perform flawlessly under such conditions; but, if combined with gravimeter measurements as described later, some meaningful results could probably be obtained.

In addition to the airborne test outlined above, ground-based GPS testing should be carried out. The object of these tests would be to investigate the potential problems facing GPS in northern latitudes, described above. It should be possible to carry out most of the tests using ground-based receivers - preferably at three or four locations, and if possible with one unit mounted on a vehicle and located at a little-used airport, so that it can travel on paved runways at speeds of at least 100 km. per hour to test the effect of movement on the performance. The precise position and elevation of the mobile receiver at any instant could be easily measured using simple equipment. Until recently, GPS receivers always used a sampling technique to collect data from several satellites. This might possibly give rise to some errors, and the modern true multichannel receivers should always be used in these tests. Analysis of the data collected over a period of a few days should make it possible to determine whether or not the potential errors outlined above are likely to give rise to major problems.

A Proposed Method of Measuring Gravity from the Air.

The state of the technology of the measurement of gravity from the air today appears to be in many ways similar to the state of the technology of gravity measurements from surface ships in 1960. The experimental results cannot be adequately explained by the current theory, and development of the technology is needed in order to achieve its full potential. The thoughts set out below may be of help in pointing out the way in the immediate future.

It is likely that the analogue cross-coupling computer, which is only necessary on the model S Lacoste and Romberg meter, limits the capability of airborne measurements. The model SL meter does not need this computer, and consequently should be used as the gravity sensor. The outputs from the gravimeter and all other measuring devices on the aircraft should be processed using digital technology, in order to minimise any possible limitations due to the accuracy of analogue technology. Furthermore, the outputs from all the sensors should be filtered digitally so that filter characteristics can be guaranteed to be identical, and the raw data should be recorded so that various filters can be tried during post-processing so as to select the best signal processing methods. In this way, the filter characteristics can be selected which maximize the horizontal resolution while adequately smoothing the perturbed data.

There seems to be no logical reason why the aircraft should be flown in any particular fashion, so long as the correcting signals are adequately accurate to compensate for any effects on the gravimeter. It is reasonable to suppose that if you can measure it, you can correct for it – no matter what "it" may be. In the early days of ship-borne gravity measurements, great efforts were made to keep the ship on a very steady course and speed; today, most observers are concerned to measure the course of the ship accurately so that corrections can be made. The same philosophy should apply to aircraft. This is especially important in the case of airships, since they have less precisely controlled movements than airplanes – just as ships have less precisely controlled movements than wheeled vehicles. In fact, it is likely that the performance of the total gravity measuring system can be assessed by its ability to operate under less-than-perfect vehicle control, and that any technology which requires the use of special autopilots, or calm air conditions, is suspect; after all, gravity can be measured from a ship with accelerations of many Gals.

It is very likely that there will be times when GPS works perfectly, and other times when pressure or radar altimeters work perfectly. A combination of two or three might be developed to be better than either; in its simplest, and possibly most reliable form, gravity measurements might be totally rejected whenever the systems disagreed by more than an acceptable amount, or alternatively the measurements might be combined using high and low pass filters. Only experimental testing can decide which is the best approach, but it seems likely that more than one altimeter will be necessary to achieve routine and reliable gravity measurements to the same standard as can be achieved today on board ship.

The gyro-stabilised platform is another component of the equipment which has the potential for causing errors which are very difficult to detect. The disturbances to the platform due to the turns of the aircraft at the end of each survey line are so great that the platform levelling control must be turned off during the turn, then the table is set to short-period mode until it has levelled, and then to its long-period, stable, mode for the observational run. This process is time-consuming and of uncertain accuracy. A digital control system would seem to have the potential of making a substantial improvement here over the standard analogue system, and could certainly make the required changes in the optimum fashion, automatically. But there remains the problem of knowing with certainty that the table is truly level, despite perturbations from the movements of the aircraft with both long and short periods. A long slow turn of the aircraft will put the platform off level and give incorrect gravity readings; presumably navigational data must be fed into the table control in order to eliminate this problem. There would appear to be sufficient information available to enable a superior control system to maintain the table level despite perturbations from all causes, but it would seem to be a substantial task to develop the system, and an even greater task to verify that it is working correctly. When flying over sea, it should be possible to use the horizon as a reference to measure the performance of the table, but over land this would not be possible.

GPS would be essential for the navigational inputs apart from the vertical velocity. It would have to be operated in the differential mode, and it seems likely that the ground station or stations should be within 200 or 300 km. of the mobile station; the maximum permissible range depends on the precision required, and should be determined during the field trials described above.

Although some data-analysis will be carried out using the airborne computer, it is certain that much more will remain to be done on the ground after completion of the survey. The equipment should be designed so as to make it as simple as possible to transfer the recorded data from its storage medium into the ground computer.

Other Factors.

Dr Makris, of the University of Hamburg, is actively proposing to measure gravity from an airship. At present his work seems to be mainly concerned with the theoretical requirements for the measurements, and he did not give the impression that much hardware has been assembled. He has no data on the performance of airships, other than a belief that they are "very smooth - like a submarine, with small accelerations". He seems to consider that the major problem facing them is in providing a power supply for the table; he is proposing a battery driven convertor, and estimates that the batteries could give two hours of operation. It was quite unclear why he was not considering a small gasoline-driven generator, since the only reason he gave was weight.

He has used a Hovercraft successfully for gravity measurements. In good weather, with calm seas, the results were good to about 1 mGal., but in substantial waves the accuracy deteriorated. Dr Makris attributed this to the common drive system for lift and propulsion - when the pilot sees a wave in front of him he increases the drive thrust so as to carry the hovercraft over the wave, and this may result in the craft dropping appreciably.

An airship, like a ship, could carry out other surveys simultaneously with the gravity survey. Bathymetric or sonar surveys would not be possible, but any of the standard airborne or satellite measurements would be feasible. These range from surface temperature measurements, and chlorophyll content of the surface waters, to slant radar wave measuring technology. It must be admitted, however, that it is not easy to think of any measurements which would warrant the intensive coverage which gravity demands, apart from the standard aeromagnetic survey – which already covers most of Canada.

Cost Factors should be given attention; the figures quoted by Bower and Halpenny are not really comparable with each other.

When comparing the costs of the various vehicles, care must be taken to ensure that the outputs from each are similar, so far as is possible. All the platforms will be affected by storms, although it is probable that the hovercraft will be affected first, and the ship last; but experience is lacking to quantify the extent of this variation, so it has to be ignored. But we also know that the existing airborne measurements require reflying about 40% of the lines, so this factor must be applied when calculating costs.

A ship suitable for gravity measurements can be chartered, on a three-month charter basis, for $10,000 to $12,000 per day. The figure of $26,000 per day quoted in the paper is the full cost of a major specialised research ship, which should never be used solely to gather gravity data. In practice, any ship carrying out a gravity survey can simultaneously carry out magnetic surveys, bathymetric surveys, and side-scan acoustic surveys. In some areas this will be of no value at all, since the data already exists, but in other areas the value of the secondary surveys may even outweigh that of the gravity survey. The ship will survey continuously, 24 hours a day, so that at 10 knots a line mileage of 240 miles, or 384 km., will be covered. It is very uncommon to need to repeat survey lines, so the cost per km. of survey is about $31 per km. All the equipment required for the survey is currently available, and is known to give results which meet the specified requirements. In addition, the ship is the only vehicle which carries all the operating staff, so that a shore base camp is not needed; all other vehicles need to travel from the shore camp to the survey site each morning, and return each night – causing unproductive travel, and a factor has to be applied to allow for this.

The only airship which is currently available, since Goodyear will not work in northern Canada, is the Skyship. The rental cost quoted by Skyship is $400,000 per month (or $13,000 per day), although they emphasised that this is only the standard figure, and should not be taken to imply that they will necessarily undertake such work, or at the same price. Nevertheless, it gives a ballpark figure. It is unlikely that airborne gravity measurements can be made for more than 12 hours a day since it is unlikely that the airship crew can keep the airship operating for longer than that, although a more intensive, but probably more costly, operation might eventually be achieved. The airship would fly at about 40 knots, or 75 km. per hour, for a total distance of 900 km. At this speed, it seems likely (based on the experience of Brozena and Gummert) that the horizontal resolution would more than meet the requirements; the accuracy of the gravity measurements has been extensively discussed above. Assuming that the base camp would not be moved more than once every two or three weeks, the average flight distance from camp to the start of a survey line would be of the order of 40 km., and the average distance surveyed would be 820 km. per day. Allowing for 40% of the lines to be reflown means that the actual distance surveyed becomes 585 km. per day, and the cost is about $27 per km. The requirement to refly lines implies that the data must be reduced almost immediately, and this would probably mean that the data would have to be sent via satellite link to the main computing centre; the cost of setting up and operating such a communications link would not be insignificant - it could very possibly add another $25 per km. One or more ground stations would be required for the GPS system, which could be expected to add $2 or $3 per km.

A small aircraft, such as a Twin Otter, with base camp support, costs about $150,000 per month (or $5,000 per day). Because it demands much more concentration from the pilot to fly it, it is not likely to average more than eight hours flying time a day, and at a speed of 80 knots - about the lowest feasible - the cost would be about $8 per km. of effective survey. The data communications and GPS requirements would be the same as for the airship, and again could add $30 per km. to the cost. The biggest problem with the small aircraft is that the horizontal resolution which can be achieved at present only barely meets the specification. This means that if the specifications are tightened at some time in the future the entire survey becomes totally valueless.

A hovercraft costs about the same as a Twin Otter, but normally operates at the speed of an airship. It should not require any resurveying of lines, and should be able to operate for 12 hours a day without too many problems. This would result in costs of about $8 per km. Data communications and GPS ground stations would not be necessary for a hovercraft, or for a ship. It is unlikely that a hovercraft could carry out magnetic or sidescan sonar surveys very effectively, and bathymetric measurements would be limited to shallow waters. But the hovercraft option looks attractive for areas of shallow seas.

The cost per km. given above allows for the reflying which has been found to be necessary in the case of airborne gravity measurements.

Conclusions (Biased) in Summary

Q. Can the present airborne gravity technology be used for surveys in northern Canada?

A. No. Brozena's measurements do not meet either horizontal resolution or accuracy requirements. Carson's measurements claim to meet the requirements, but the only hard information available seems to indicate that the actual performance is not as good as is claimed.

Q. Can the present airborne gravity technology be developed to the standard required?

A. It is not possible to give a firm answer to this, but there is no reason to believe that the technology cannot be developed. How long it will take, and how much it will cost, are unknowns - but by analogy with marine gravity systems, a decade would seem to be a reasonable time.

Q. Can Airships be used as platforms for gravity surveys?

A. There is no reason to suppose that they would be worse than a heavier than air craft, and many reasons to suppose that they would be better. But there is no hard data to back up this intuitive statement. The costs are rather high, they are definitely not suitable for surveys in mountainous areas, and they are not in plentiful supply. But, apart from helicopters, they are the only aircraft which can clearly meet the horizontal resolution requirement, and helicopters are more expensive to operate than airships.

Q. Are airships necessary for the areas listed as requiring survey?

A. No. Foxe basin could be surveyed by Hovercraft; Hudson straights, Cumberland sound, Ungava Bay, the Northern part of Davis Straight, and the Pacific could all be surveyed by ship, which would simultaneously generate bathymetry data which is needed for all these areas. The rocky mountains present a challenge for anything other than pack-mules.

Q. Would airships have advantages over ships?

A. Yes, they might be cheaper if only gravity were measured.

Q. Would airships have disadvantages as compared to ships?

A. Yes, since a ship is a self-contained community, whereas the airship needs to have ground support camps set up for everyone involved in the operation. This implies a great deal of careful organisation, such as that required for Polar Continental Shelf operations. Furthermore, gravity can be measured from ships today, whereas airship technology needs to be developed.

Q. Apart from the fascinating challenge of airborne gravity, is it reasonable to develop the system?

A. For Canada by itself - probably not, since the costs would be extremely high. But it must be recognised that Canada already has the expertise required for much of the development, with GPS expertise in UNB, shipboard gravity expertise in two areas of GSC, and good contacts with the Gravimeter manufacturers. Furthermore, Canada has always been a world leader in geological and geophysical survey technology, and there is every reason to encourage this to continue. A great deal of valuable experimental work could be done at very little incremental cost, by using resources which are available, if leadership is provided by an interested individual. Experimental work on the GPS system could be done using existing equipment (although the new receivers which are now available would give much better results), if it was deployed in the field by groups already engaged in appropriate geographical areas, the results being analyzed by the U.N.B. group. This approach would be especially valuable as a means of gathering and analyzing data in arctic regions. Further GPS experiments could be carried out using one or more aircraft; the U.S. Convair could very probably be made available if Dr. Brozena were invited to be part of the team developing the system, or a Canadian Government plane, preferably a Twin Otter or similar, could be used. Development of the gravity system could be carried out using the Earth Physics Branch straight line gravimeter, the U.S. Convair, and the digital analysis system being developed by Dr. Valliant at Lacoste Romberg; this would require extensive cooperation between the several groups and organisations, but in the light of the interest expressed to the author of this report, such cooperation would seem very possible. These investigations could answer virtually all the questions raised in the report, so that definitive proposals could be made for substantial surveys for specific areas.

Q. Assuming that airship gravity is to be followed up further, what steps should be taken to achieve this?

A. The main problem appears to be the measurement of vertical accelerations of the airship; differential GPS experiments should be carried out, first using three or four receivers on the ground in southern Canada, then in the Arctic (as described above), then perhaps on a tethered balloon. Then the precise comparison between pressure altimeter, GPS, and laser altimeter described in the text should be made, preferably using an airship but possibly using an aircraft. Then, and only then, should experimental work start using a gravimeter carried on an airship; making careful measurements over one or more test ranges, one preferably being in the Arctic, before starting on the surveys themselves.

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M. Casey	Can. Hydrographic Service, 615 Booth St. Ottawa	613-992-0017
Dr. L. Collette	G.S.C., Observatories Bdg., Ottawa	613-992-7955
Dr. J. deLaurier.	Inst. for Aerospace Studies, U. of Toronto, 4925 Dufferin St., Downsview	416-667-7708
W. Gummert	Carson Geosciences	215-249-3535
Dr. D. Hardwick	N.A.E., Ottawa	613-998-3525
Iverson	Engineering Service Associates, 1500 Massachussets Ave.N.W., Washington	
Dr. D. Jones	U.S.A.F. Mapping Div., Bolling A.F.B., Washington	202-767-6102
A. Kleusberg	U.N.B., Fredericton	
Dr. J. Kouba	G.S.C., Observatories Bdg.	613-995-5302
Dr. J. Makris	U. of Hamburg, Germany	404-123-3969
Capt. D. Minster	U.S.A.F., Bolling A.F.B., Washington	202-767-1289
Mr. Morphan	Airship Industries, U.K.	234-741-901
S. Nelson	Office of Oceanog. of Navy, Washington	202-653-1552
D. Philips	Carson Gravimeters	512-429-7330
R. Sailer	Goodyear Aerospace, Akron, Ohio	216-796-2995
L. Stohr	American Blimp Corp., 18908 13th Place S., Seattle 98148	206-241-7422
R. Sutherland	Can. Engineering Services, Edmonton	403-438-1336
Dr. H. Valliant	LaCoste and Romberg, Austin, Tex.	512-346-0077

Mrs. J. Vocar	Loral Defence Systems, Akron, Ohio	216-796-8655
Dr. D. Wells	U.N.B., Fredericton	506-453-4698

Useful Addresses, etc.

	Airship Industries, New York Airship Industries, London, U.K.	212-262-7230 1-995-7811
	Bradley Air Services, Resolute	819-252-3981
C.Mills	Dept. Agriculture, New Jersey	201-349-8905
A. Hixon	Magnus Aerospace Corp., 141 Laurier W., Ottawa	613-236-4798
Dr. C. Jekeli	Hascon A.F.B. (Balloon Gravity Measurememnts)	617-377-3486
K. Jones	Zeppelin International, Arlington	
F. McGovern	Winship Aviation, Edmonton	403-436-6418
Dr. T. Rooney	Hascon A.F.B. (Balloon Gravity Measurememnts)	617-377-3486
H. Warner	Cameron Balloons Canada Lighter than Air International, Twin Atria Bdg., 4999 - 98 Ave., Edmonton, T6L 5H3	403-258-1997 403-422-4486
R. Ziegler	Defence Mappng Agency (Gravity Gradiometer)	703-285-5383

Notes from Discussions

Wells and Kleusberg, U.N.B.

Cycle slips do not matter in determining velocities, since the 'erratic' velocities, implying impossible accelerations, can be rejected. Also if more than 4 satellites are in view, the redundancy can be used to detect and correct cycle slips.

Jouba's estimate of vertical acceleration error for GPS is based solely on a 2 mm. random jitter; the results are purely theoretical, but do indicate the minimum filtering needed.

Measurement of actual GPS performance isn't going to be easy. Agreed that probably the airborne part of the test should use a lake 10 km. long to get a level reference surface - either windless or better newly frozen with no more than a dusting of snow - and repeated flights with ground stations close and remote.

GPS is currently only available for a couple of hours. Complete set of satellites may be up in 1 or 2 years. Orbit data is currently not downgraded but actual accuracy is not as good as predicted. If deliberate downgrading is introduced with complete system, the present accuracies may not be available at all; or full data may be released with a 2 week delay. Additional ground stations might theoretically overcome any problems from this source, even in real time.

Errors from the ionosphere, in arctic regions, can give rise to large perturbations. Relative position errors of up to 1 metre may arise, and rapid variations of several decimeters, with periods of minutes. Effects are localised and not common to ground stations and mobile. Correcting by dual frequency analysis reduces this by 75% (see Wells et al, 9.6)

Problems with matching filters for GPS data with gravimeter filters must be watched.

Use of switched multichannel receivers such as TI-4100 may well accentuate cycle slip problems and measurement noise. Multichannel receivers such as Ashtech and SNR-8 are probably better.

Tropospheric effects may well be problems. Troposphere is not dispersive and dual frequency analysis cannot help. Effects (total) are about 5 metres, and use of tropospheric models can still leave 5-10% of this this. Variations in water content and atmospheric density in the paths to mobile and fixed stations can give problems.

Brozena, U.S. Naval Research Lab.

Altitude is primarily obtained from radar altimeter; pressure measurements very often have long period waves which obviously affect results.

Long period horizontal accelerations, such as when aircraft is in a slow turn, have been observed to affect gyro and cause errors from off-levelling.

No-one has used 84 minute gyro, to his knowledge.

Does not know precisely what the radar altimeter is measuring - height above troughs of waves, or peaks, or some average.

Autopilot is critical part of equipment. Was specially built and adjusted, starting from a very high-quality commercial autopilot.
Radar altimeter is specialised piece of equipment, built up from standard commercial items, which gives extremely precise measurements.

Gravimeter used is a type S Lacoste and Romberg marine gravimeter, with its normal analogue cross-coupling correction computer. The accuracy of the measurements are possibly limited by the cross-coupling corrections, since the analogue computer limits at a fairly low value of correction. The autopilot has been tuned so that the flight path is very smooth and consequently the cross coupling corrections are small.

Brozena would be interested in participating in gravity measurements from an airship, using his Radar altimeter as the primary altitude sensor but with air pressure sensor fitted as well.

Fights have been made with altitude measurements made using both Radar altimeter, GPS (using TI 4100 receivers), and air pressure sensors. The data from the flights are awaiting analysis. Four flights were made, only one of which had all systems functioning. Comparisons between Radar and GPS show that if the data is filtered through three stages each with more than 40 sec. time constant, good agreement is obtained.

Data from flights are rejected if the instrumental outputs appear abnormal. The skills needed to decide whether to accept or reject measurements take time to aquire, and involve the consideration of several indicators.

The accepted data is subjected to expert review, and data-processing and data analysis is used to improve data quality. Brozena implied that this gives rise to much greater time constants than those in the gravimeter circuitry; perhaps 15 or 20 km. resolution for the P3A, 5 km. at 80 knots in the Twin Otter.

The pressure altimeter sensor output, filtered though a 2 Hz. filter, gives a noise signal of the order of 1 mV. when the aircraft is on the ground. The output is 10 V. for 300 mbar. change in pressure, so that 1 mv. corresponds to about 25 cm.

The pressure altimeter has very often been found to have long period waves.

Gummert, Carson Geosciences.

Explained that Carson Helicopters had developed their techniques for measuring gravity from the air over many years, and that recovering their development costs required them not to disclose their methods, in order to avoid rival companies from exploiting their work (as had occurred in the field of airborne magnetics)

They use a pressure sensor extensively; originally they used helicopters exclusively, fitted with a probe mounted ahead of the aircraft, similar to that used by Brozena. They discovered that a probe mounted above the main rotor, coaxial with the rotor shaft, gave results as good as the front-mounted probe.

In recent years they have used a Norseman aircraft; costs are much less than for a helicopter, but resolution (horizontal) is much worse.

They have done most work for oil companies, surveying in areas which cannot easily be reached on the ground; requirements tend to be detailed in terms of horizontal resolution, requiring slow speed flying.

They use intensive selection of field data in order to obtain good data for the final chart.

They refly 25% to 50% of the total lines flown, as well as running the usual cross-check lines.

They subject the data to intensive data-manipulation.

Carson Geosciences has patents on airborne gravity measuring technology, in many countries.

When discussing the differences between the two Bouger maps in their brochure, claimed that the discrepancies were due to the upward extrapolation of the ground level gravity field to the flight altitude. In addition, mentioned that the ground-level data is not always reliable, as was found in flying over test ranges.

They fly as low as possible, compatible with the terrain and general safety considerations.

Stressed that it is essential to have a specially developed autopilot, since manual flying cannot produce any useful data.

Use the same gravimeter set-up as Brozena.

Believes no-one has ever used an 84-min. platform due to excessive wandering.

Has flown many test trials against ground surveys. Some organised and supervised by Oil Companies, some independent. Also testing on the S. Carolina test range. Specifically mentioned an extended and detailed test over a range in Pennsylvania, sponsored by 10 major oil companies. All tests achieve satisfactory results. When doing contract work, always allows staff of the customer to supervise all aspects of the work in detail.

Would be very willing to undertake more ground-truth tests, either over land or over sea. Could work over the Arctic Ocean, and made proposals to do so to U.S.Navy, proposing to use a turboprop DC3.

Looked into possibilities of airships as gravimeter platforms some time ago. Attractive because of economy and ability to operate at any speed, like helicopter. Feels that airships would not be easy to operate in the isolated jungle areas which they survey. Was concerned about vertical movements, and said that the French measured vertical accelerations on board airship and decided to abandon further work as a result. Could not recall any details of these experiments.

Interviewed 1,000 airship pilots, and decided as a result that they bounce through the sky.

Airships do not have autopilots, and are not controlled in the same manner as are aircraft. At some time in the past, a group was rumoured to have been considering fitting an airship with airfoils and a control system like that of a submarine.

Would be happy to carry out surveys on a commercial basis for the Canadian Government, and would be willing to negotiate rates.

<u>deLaurier, Inst of Aerospace Studies, U. of T.</u>

Has ridden in Skyship 500 and considered the ride to be "very smooth". In the mountains, wind gusts have caused violent motions with accelerations of up to 1G. Believes that airships and aircraft behave fairly similarly; remember that comparisons should be made between vehicles flying at comparable altitudes - a high-flying jet behaves quite differently from a plane flying at 500 metres.

Theoretical calculations show accelerations of up to 0.3G. for severe wind gusts.

Has done a great deal of theoretical work on the behaviour of airships, including transient response to controls, perturbations, etc. Many publications in this field.

Does not know of any airship fitted with an autopilot.

Airships behave like ships when making a turn; they turn their axis to the new direction, and then move in the original direction for a substantial period, skidding sideways through the air or water. Airplanes respond in a manner more like that of a wheeled vehicle.

Theoretical data shows that an airship is about critically damped for all motions except roll. If a lateral horizontal impulse is applied, the airship is displaced sideways and usually also turns; both movements are critically damped. But if the simulator is designed so as to return the vehicle onto the original course, an induced oscillation with a period of about 30 secs. will appear.

The U.S.Navy attempted to reach the North Pole in a Navy Blimp a few years ago. Brigadier-General Keith Greenaway has details of the expedition. It was abandoned part way, because of severe problems with icing of the airship.

Anti-icing sprays now exist which are very effective.

Airships can fly in weather conditions which ground small aircraft.

Is carrying out theoretical studies for the American Blimp Corporation, of Seattle, Washington.

American Blimp are planning to make measurements of accelerations experienced on an airship in both calm air and in turbulent conditions. Experiments are planned for the area south of Seattle, in the spring of 1989.

<u>Valliant, LaCoste & Romberg.</u>

Believes cross-coupling is negligible in aircraft. Said Gummert has confirmed this.

Said that Gummert's criterion for good data is that the analogue output trace from the cross-coupling computer should be a straight line. Valliant believes that corrections are possible, and that the straight line criterion should not be necessary.

Has participated in two airborne surveys, but considers his experience limited.

Agrees that the analogue cross-coupling meters have limited range for a given accuracy.

Feels that both Brozena and Gummert have extensive experience, and knows that they reject data on the basis of "intuitive" feelings.

Feels that high-pass filtered barometric data merged with low-pass GPS data could give good results.

Is currently involved with improved digital control and processing circuitry, similar to that developed in Ottawa but better, and believes that such a system should give good results if used in aircraft.

Tests he did in Canada were good. Was trying to get input data for Eotvos correction from the platform, and was getting gravity to 2 or 3 milligals without a special autopilot. Also tried connecting gravimeter output to the autopilot control input, to get steady flight.

Wonders whether Carson may lean toward emphasising difficulties and problems, in order to discourage competitors.

Has read reports that the ride in old German airships was very smooth - a nickel could be stood on edge on a table for extended periods. (N.B. this steadiness is comparable to a submerged submarine). Has heard that new airships are like riding a bucking bronco, and especially that flight over a city gives a turbulent ride, whereas over the sea is smooth.

Is personally very interested in airship measurements, but does not know what the attitude of the new owner of LaCoste and Romberg would be.

Bodger, Scintrex

Scintrex manufacture Geophysical survey instruments, and their gravimeter might be suitable for conversion to an airborne device. They have been holding discussions with G.S.C. about new applications for the gravimeter; but feel that financial support would be needed for such a development.

Philips, Carson Gravimeters.

Carson gravimeters are involved in the repair of both land and sea gravimeters, plus the construction of new electronics, modifications, etc. Currently building a graphite platform with new electronics, so as to get weight down to a minimum.

Bernfield, Bell Aerospace.

Feels that the marine area between the shoreline and sea which is not deep enough for a normal survey ship is not covered by current technology.

Raised the problem of horizontal resolution when using aircraft.

Does not know of anyone planning measurements from airships.

Iverson, Engineering service Associates.

Was on 1967 Polar trip with Neil Andersen; still in touch with him.

Believes there are many people in Washington who are knowledgeable abou airships; mentioned NADC, near Carson Helicopter; also Charlie Mills, working for the Department of Agriculture on the Piesaky program in New Jersey.

Navy had a program, until last year, to look for airship to provide long-range radar coverage for each fleet (6 in all). E.S.A. put in a bid on this project.

All his airship files are now in storage.

Has been associated with Gummert in helicopter gravity measurements. Mentioned French tests as being unsuccessful, "due to problems similar to those which Carson encountered with helicopters". Does not feel that motion problems are insurmountable.

Stated that Gummert had tested a straight-line meter side by side with an S meter, but found no difference.

Would not recommend Bell meter; Gummert and he bought Bell #1 when they were at the Army Map Service, and tested it extensively - it seemed to work well on board ship.

Airship Industries is just about the only firm around which is promising,in his view. There is also a company in Tennessee with a small airship, and a remote-controlled unit in California (thought to be very small)

Makris, U. of Hamburg.

Is interested in the possibility of gravity measurements from airships, and has carried out studies but nothing more applied.

Believes that the German Geodetic group have developed computer programs which would be adequate for all positioning requirements from GPS system. But discussions indicated that this refers to the software only, and he was unsure as to whether there has been any actual experimental testing.

Has no data on Airship movements, but believes that they are very smooth, like a submarine, with small accelerations. He would propose a Skyship 2000 to carry his Bodenseewerk meter (but says he may not have the correct name of the airship). They have problems with the power supply for the table. It requires 400 Hz. power, and they are developing a battery-powered supply, due to the limited power available from the airship's electrical system. Batteries would give a 2 hour endurance; the weight of an independent power generator would be too much for the airship.

Has made measurements on hovercraft. The data was good in calm water, but not in rough seas. Difficulties were ascribed to the control system of the hovercraft - the normal hovercraft has a single power unit which drives both the lift fan and the horizontal drive, and the pilot normally accelerates to 'rush' a wave, thereby affecting the height. Accuracies of 1 mGal. were achieved in calm water.

Morphan,Airship Industries.

Airship Industries mainly use their Skyships for advertising and tourist sales. They have fleets operating based in the U.S.A. and in Europe (mainly England) and would be happy to quote on specific charters for operations anywhere - except that they are pretty well fully booked for 1989. Normal charter cost for a Skyship 600 is £200,000 per month.

Sailer, Goodyear Aerospace.

Goodyear was the target of a hostile takeover in 1986. They survived the attempt, but in the process divested themselves of the Aerospace Division, which manufactured the Goodyear Blimps, to Loral Systems Group.

Goodyear continue to own and operate Blimps, but get spare components from Loral.

Their Blimps are not available for use in the North - Ontario in the summer is the farthest north they will go. Snow and ice are the reasons for not going north, since they "can crush an airship (dirigible) like an eggshell".

Sutherland, C.E.S.

Soliciting support for an experimental venture to promote airships as instrumentation platforms.

Has participated in gravimeter surveys on land.

Believes that he can produce a super altimeter, not based on GPS, accurate enough for gravity measurements from airships. (I indicated that if he could substantiate that in his proposal to the Government for developmental funding, there would certainly be support from the Canadian gravity community).

Believes that airships are very smooth-riding

Is planning on making a proposal to detect submarines under the ice by gravity measurements from the air.

Vocar, Loral Systems Group.

Loral is uncertain what its future will be; but there are no plans at present to build airships.

Stohr, American Blimp

Stohr is project engineer at American Blimp.

First unit was flying last year; now taken down.

Hope to have three airships flying this summer.

They are planning instrumented test fights this summer, including measurements of accelerations. The data is intended for development of their airships, and so will be confidential, but they would consider releasing specific parts for particular purposes.

Does not believe that anyone has ever fitted an autopilot on an airship, and is doubtful if they ould do so, since the Pilot can get leave the controlss and walk about for two or three minute periods leaving the airship to fly itself.

Claims their airship is more stable than any other ever made.

Bradley Air, Resolute

Twin Otter charter rate is around $83,000 per month, plus fuel, plus ground support.

**STATEMENT OF REQUIREMENTS:
INVESTIGATION INTO THE FEASIBILITY OF AIRSHIPS
FOR AIRBORNE GRAVITY SURVEYS**

1. Purpose

The primary purpose of this study is to investigate theoretically the merits of airships relative to other types of aircraft for gravity measurements, and to assess whether flight tests are warranted.

A secondary purpose is to identify other types of airship observations that might be compatible with gravity operations, e.g. aeromagnetic mapping, magnetic gradiometry, E/M sounding, laser bathymetry, through-ice bathymetry, oceanographic remote sensing, etc. For this purpose, it will be necessary only to enumerate the possibilities that come to light in the pursuit of the study's main objective; detailed investigations of these supplementary techniques will not be required as part of the present investigation.

2. Method

The investigation will be divided into two phases: a primary phase to determine the feasibility of airship use, and an optional secondary phase to determine optimum vehicle configuration, costs, and the availability of suitable airships.

Phase I will focus on the identification and assembly of available information under the headings shown in Appendix A. It is recognized that not all relevant factors may be identified in that list, so the investigator will be asked to remain alert for other issues, and to bring them to our attention.

Most of the information in Phase I should be obtainable through discussion with various experts (see Appendix B for suggested contacts) and through perusal of the literature. Much of the work will involve telephone and mail contacts, however it is expected there will be a need for visits to one or more centres of expertise for detailed research and discussions.

The decision to proceed with Phase II will depend on the outcome of Phase I, and separate specifications will be issued at that time. In brief, if airships appear promising for gravity work, the investigator will be asked to gather information according to the preliminary outline shown in Appendix C, and to prepare a follow-up report.

3. Deliverables

The results of Phase I will be presented in a report that summarizes the outcome of discussions and literature searches, and identifies the sources of information. The report should contain a discussion about the feasibility of using airships for gravity work, as compared to helicopters and fixed-wing aircraft, and should indicate whether future investigations (including test flights) are warranted. The prospects for compatible observations should be addressed also, in the form of a list or catalog that itemizes operations that could be carried out concurrently with gravity work.

4. Background information

4.1 The case for airships

Airborne gravity observations are now routinely collected aboard helicopters and fixed-wing aircraft operated by at least one private operator in the USA (Carson Helicopters), and by the Naval Research Laboratory (NRL), a civilian arm of the US Navy.

Each type of aircraft has its advantages and disadvantages: helicopters can offer high resolution by flying at slow speeds, but they have limited range and endurance, with a low payload-to-cost ratio; fixed-wing aircraft can carry bigger payloads over longer times and distances, but their higher speeds result in poor resolution on account of the long distances travelled while the gravimeter output is being filtered.

By combining the best features of both types of aircraft, - low speeds, long range and endurance, large payloads - airships may offer a superior alternative for airborne gravity measurements.

4.2 Accuracy considerations

On fixed-wing P3 aircraft, the existing technology and procedures for airborne gravimetry are reported to yield observations with accuracies of 2-3 milligals, resolving features in the gravity field that have wavelengths of 10 km or more (Brozena, 1988). Helicopter techniques are claimed to give sub-milligal accuracies over much shorter wavelengths (Hammer, 1982), limited largely by the time necessary to do the high-resolution measurements, and by how much the customer is willing to pay for such work.

To be worthwhile to marine interests in the GSC, airship gravimetry must yield observations that are equal to or better than those presently obtained aboard survey and research vessels operating in the open ocean, i.e. accurate to one milligal or better, with a resolving power of 1-2 km or less. This would be suitable for most reconnaissance applications.

It is probable that technical refinements will lead to greater accuracies and improved definition of the gravity field (in fact, Carson Helicopters are now delivering that kind of service to a specialized, but worldwide market).

For the GSC, the primary focus right now concerns broad regional surveys; high-resolution operations are not an immediate priority, but these could well increase in importance once the capabilities of the new technology are developed and recognized.

4.3 Areas of operation

Aerogravity is well suited for systematic mapping operations in oceanic regions, especially where ice, climatic, and oceanographic conditions make it impossible, too expensive, or too time-consuming to perform conventional gravity operations (e.g. underway surface observations, or spot measurements on the ice and sea floor). There are several such areas of interest to Canada: Ungava Bay, Foxe Basin, Baffin Bay, Kane Basin, the Arctic Ocean.

The technique could also serve as an economical means to map the vast oceanic regions where gravity remains poorly delineated.

With proper altitude control, the aerogravity method can also be applied to the mapping of selected land areas where the topographic relief permits flight levels that are low enough to yield the desired measurement resolution e.g. the Greenland ice cap.

4.4 Navigation considerations

The most important problem in navigation for aerogravity is the accurate determination of vertical accelerations. This and related topics are being investigated separately.

Navigation over land areas and ice-covered water will probably require the integration of outputs from two systems: dynamic GPS interferometry, and inertial navigation (the latter may be obtainable as a ready by-product of the gravimeter's stable platform). This approach should eliminate or at least minimize dependence on ground-based navigation systems (although stationary GPS receivers will be required for interferometric observations; these may form part of a pre-existing network).

Over open water, navigation requirements are simplified substantially because vertical accelerations can be measured with an accurate altimeter. Horizontal positioning still relies on GPS-INS integration, but minus the operational complexities of dynamic GPS interferometry.

5. <u>Bibliography</u>

Brozena, J.M., and Peters, M.F. 1988. An airborne gravity study of eastern North Carolina. Geophysics, v. 52, p. 245-253.

Hammer, S. 1982. Airborne gravity is here! Oil & Gas Journal, January 11, 1982.

November 17, 1988

APPENDIX A

PHASE I TOPICS

1. **Airship operating characteristics**

   stability
   speed control
   horizontal and vertical maneuvering
   horizontal and vertical acceleration spectra
   range and endurance
   operating altitude

2. **Facilities for carrying and operating instrumentation**

   payload capacity (current system configuration weighs between 1000 and 1500 pounds)
   power (system currently draws 5KW)
   internal environmental control (temperature, pressure, etc.)
   operator accommodations (two operators on flights up to 12 hours' duration, three on longer flights)
   autopilot
   support systems (i.e. navigation and communications)
   external sensor arrangements (GPS antenna mounts, optional magnetometer sensors, provision for altimeter installation)

3. **Other sensor systems**

   devices that can be operated concurrently with gravity systems

4. **Logistics and support requirements**

   mobilization and demobilization
   operating bases
   fuel supplies
   maintenance needs
   ground crew

5. **Operations in Arctic regions**

   Ability to cope with weather and visibility conditions, as well as extended flights over land and sea areas covered with permanent or semi-permanent snow and ice

5. **Other constraints**

Restrictions not addressed in the foregoing sections (operating regulations, etc)

6. **Experience of other agencies**

Previous activities involving: precise navigation (especially the accurate determination of vertical accelerations); the operation of gravimeters or other advanced instrumentation, deployments in polar regions, etc.

APPENDIX B

SUGGESTED INITIAL CONTACTS

1. **John Brozena**

   US Naval Research Laboratory, Washington, DC. (202)767-2024

   Main player in NRL's airborne gravity work since 1980. Is knowledgeable about the operational requirements and limitations of gravimeters and aircraft. Can suggest further avenues for airship investigations.

2. **Doug Hardwick**

   National Aeronautical Establishment, Ottawa, ON. (613)998-3525

   Convair 580 Project Manager. Knowledgeable about airborne geophysics, has participated in most discussions so far concerning aerogravity. Has access to airship expertise through NRC colleague who was involved in (unsuccessful) negotiations a few years ago when the Government sought to lease an airship for evaluation and demonstration.

3. **Bill Gummert**

   Carson Helicopters, Philadelphia, PA. (215)249-3535

   Successfully operating a commercial aerogravity service using helicopters and fixed wing aircraft. Involved in early efforts to develop airship applications for the earth sciences.

4. **Len Collette**

   Geophysics Division, GSC, Ottawa ON. (613)992-7955

   R&D consultant to Director of the Geophysics Division. Authority on airborne E/M; very knowledgeable about potential airship applications, as well as mechanisms for promoting industry/government interactions in this area.

5. **Alan Goodacre**

Geophysics Division, GSC, Ottawa ON. (613)995-5458

Head of Instrumentation Section. Can provide history of GSC's technical and engineering developments for aerogravity, can also provide material developed during feasibility studies (or contacts with individuals who carried out the studies).

6. **Mike Casey**

Canadian Hydrographic Service, Ottawa, ON. (613)992-0017

Development officer. Participant in initiatives to develop capabilities for airborne bathymetric mapping. May have engineering and technical requirements similar to those for aerogravity.

7. **Jannis Makris**

University of Hamburg, Hamburg, Germany. 040 4123 39 69

Director, Institute of Geophysics. Apparently planning an airborne program using a C-130. Reported to have operated a KSS-30 gravimeter in an airship.

8. **Mel Best**

Atlantic Geoscience Centre, Dartmouth, NS. (902)426-2730

Head, Eastern Petroleum Geology Subdivision. While with Shell, led investigation into use of airships for E/M work, almost culminating in lease of Goodyear blimp.

9. **Ray Sutherland**

Sutherland Airship Corporation, Edmonton, AL. (403)438-1336

President. Active proponent of commercial airship services. Through parent company (Canadian Engineering Services), was involved a few years ago in abortive attempt to lease a British airship for pilot and demonstration purposes in Canada.

11. **Arthur Darnley**

Geological Survey of Canada, Ottawa, ON. (613)995-4909

Has studied airship potential for airborne geophysics, has contacts in Canadian Gov't who could contribute knowledge, advice, and support.

12. **Jim De Laurier**

Institute for Aerospace Studies, Downsview, ON. (416)667-7708

Knowledgeable about history and technology of lighter than air platforms. Has worked with USAF in balloon-borne microgravity studies.

13. **Gravimeter manufacturers**

May be able to offer leads on who else is contemplating similar initiatives, or may be able to provide some direct input into the investigation:

Norm Bernfield
Bell Aerospace, Buffalo, NY. (716)297-1000

Dr. Berkhahn
Bodenseewerk GMBH, Meersburg, W. Germany. (07532)8010

Durwood Philipps
Carson Gravimeters(?), Austin TX. (512)459-7330

Herb Valliant
LaCoste & Romberg, Austin, TX. (512)346-0077

Tim Bodger
Scintrex, Concord, ON. (416)669-7280

APPENDIX C

PHASE II TOPICS
(Preliminary outline only)

1. **Airship models best suited to the work**

   size
   make
   configuration
   manufacturer's expertise and previous involvement in comparable activities

2. **Sources of airships and/or airship services**

   manufacturers
   private leasing operators
   foreign governments

3. **Cost**

   lease vs purchase
   mob/demobilization
   field and operating expenses