Polar Navigation for Research: Then and Now

The highest latitudes offer many challenges to navigation. Dr. John K. Hall, whose Arctic career began on drifting scientific ice station Fletcher’s Ice Island (T-3), examines the progression from celestial navigation through Transit satellites, and how GPS enables new research from his innovative arctic research hovercraft, the R/H Sabvabaa.

I was very fortunate to have had the opportunity to do my doctoral dissertation on the marine geophysical studies carried out from Fletcher’s Ice Island (T-3) between 1962 and 1970. This was part of Columbia University’s Lamont-Doherty Geological (now Earth) Observatory’s participation in the drift of Ice Island T-3. T-3 was a 90 km² and 50 m thick slab of glacial ice, probably carved from the glacier exiting Yelverton Bay on northern Ellesmere Island. First occupied by the US Air Force as a weather station in 1952, T-3 (the name denotes the third such target identified by B-29 aircraft radars) was an American research station during the 1957-58 International Geophysical Year (IGY), and subsequently operated by the US Navy’s Office of Naval Research from 1962 to 1974. Altogether T-3 was occupied during four occupations, three by the US Air Force for 2631 days, and once by the Navy for 4606 days, for an unprecedented total of 7,240 days, a record far exceeding that of any other Russian, American, Canadian, and European ice stations.

My dissertation included continuous echo-soundings, magnetic field measurements, and periodic gravity measurements, as well as some 4,000 km of continuous seismic profiling as the ice station drifted some 20,000 km at an average rate of 5 km/day in the clockwise Beaufort gyre of the Amerasia Basin north of Alaska, Siberia, and the Canadian Archipelago. My duties also included compilation of the drift track, initially by celestial observations, and from 1967 by use of one of the first US Navy Transit AN-SRN-9 receivers for the Navy Navigation Satellites System.

Celestial Navigation

Celestial observations were made when possible using a Wild T-2 theodolite with four power telescope, mounted on a solid wooden timber embedded deep in the glacial ice. This was protected inside a small square plywood enclosure with a door and four hinged triangular roof sections that could each be swung down to reveal quadrants of the sky. The track of the ice station during those years varied from about 75° to 86°N, thus ensuring up to four months of complete daylight and night, with spring and summer periods of both day and night. Star observations at night allowed almost instantaneous and quite good fixes to be obtained, from as many as five navigational stars. This required the observer to take five stopwatches and a clipboard out to the theodolite hut in temperatures to -40°C.
Taking care not to breathe on the theodolite (resulting in ice crystals on the optics), nor to allow the eye socket to touch the eyepiece (resulting in frostbite and the likelihood of bonding to the cold metal), altitudes and azimuths were measured and recorded on each of the up to five properly identified stars, with the stopwatch being started at the instant of each observation. The theodolite zero-azimuth (called the island azimuth) was set on a fixed landmark in the camp (flag pole) and care was taken to maintain its level through checking of the bubble levels.

Figure 2: The camp on T-3, the 90 km² ice island occupied for some 7,240 days. The buildings in the foreground are on thick glacial ice, while the hydro-huts in the background are on 3 m thick sea ice. The domed trailer and small peaked shack with pointed roof at far right are the geophysical lab and theodolite shack shown in Figs. 3-6.

Working up the fix then consisted of determining the exact GMT of the each observation, by reference to a ship’s chronometer, whose drift was measured by reference to periodic comparisons with the WWV time standard on a shortwave radio receiver. The celestial altitudes were then corrected for refraction according to the temperature and barometric pressure based upon extrapolation of the American Nautical Almanac values, and later based upon observations by the Pulkovo Observatory in Leningrad kindly provided by Dr. Raynor L. Duncombe of the Nautical Almanac Office at the US Naval Observatory. These, along with each star’s computed local hour angle (LHA) according to the time of observation and its Siderial Hour Angle (SHA) from the American Nautical Almanac, were used with the American Sight Reduction Tables, to produce lines of position on a preprinted plotting sheet. With two to five intersecting lines of position, the ice island position could be determined to an accuracy of 0.1’. The measured azimuths allowed determination of the island azimuth and therefore the orientation of the station’s 3000 ft ice runway, important knowledge for pilots coming in for a night landing under less than ideal conditions. Under certain conditions of cloud, haze, snow flurries, observations of the Moon’s upper or lower limbs were also useful.

For the summer period, navigation was considerably more difficult, being contingent on clear visibility of the Sun’s upper and lower limbs and the need for a series of observations several hours apart in order to obtain 30° or more of intersection between the various lines of position (LOPs). Observations of the upper or lower limb of the Sun through a four poser telescope were not for the faint-hearted; at age 70 I still have a left eye seeing a slightly darker image than my right. Unfortunately we never had a Roelofs solar prism, which folds the Sun on itself so that an exact measurement of its centre is possible. This would have eliminated the need for a solar diameter (SD) correction, which is strongly dependent on atmospheric refraction. Daytime observations of the Moon were also useful. Periods of strong daylight make for wonderful photos of the Arctic landscape, but are often only available between long stretches of obscured sky.

In analysing some 7,000 celestial observations to obtain the drift track between 1962-67, I abandoned the manual recomputation and plotting of the fixes and turned to the new IBM 1130 (16k memory) installed at Lamont. With help from Dr. Duncombe and the equations for solving position through spherical trigonometry and computing the ephemerides of the stars, Sun and Moon, I wrote programs in FORTRAN IV to provide fixes from these observations. Because of the much improved precision and stability of the theodolite over a handheld nautical sextant (0.1 sec of arc versus 0.1 min), the computer vastly improved these fixes over those computed on the station.

To obtain the overall hourly drift between fixes, I then tabulated the hourly wind speeds and directions measured by the U.S. Weather Bureau team on T-3. Dr. Vagn Walfrid Ekman (1874-1954) had determined empirically from observations made during Fridtjov Nansen’s 1893-96 drift of the vessel Fram that ice drift in the northern hemisphere is about 1/50 of the wind speed and 20-40° to the right of the wind direction. Accordingly another FORTRAN program was written to use the fixes and the wind data to produce hourly estimations of the position, by using least squares to solve both for the fraction of the wind speed and the angle to the right of the wind direction. The longest period without a fix was 22 days, and the fastest drift was 22 km in a single day. These hourly positions were of course best approximations taking into account that the ice pack is also under the influence of regional pressures.

These FORTRAN IV programs are accessible from page 106 of my PhD thesis at: http://www.polarhovercraft.no/uploads/Main/Hall-PhD-thesis.pdf.

Figure 3: The author shooting the Sun’s upper limb with a Wild T-2 theodolite.

Figure 4: The author tuning the home-built Transit navigator onto a passing Transit satellite. Because of our high latitude (around 86°N here) up to 52 fixes could be logged each day.

Satellite Navigation - USN TRANSIT Navigation Satellite System (NAVSAT)

In the spring of 1967 one of the four satellite receivers home-built at Lamont arrived at T-3. It was based on an AN/SRN-9 satellite navigation receiver which integrated over two minute periods the Doppler shift of a satellite broadcasting at 400 MHz, which passed from horizon to horizon. It was a large console with a washtub-sized rooftop conical antenna with whip and ground plane. A modified Friden calculator was used to print out up to ten Doppler counts, as well as slowly repeated ephemeris data describing satellite’s orbit. Because the Transit system used ten satellites in polar orbit, with a repeat time of 106 minutes, we were able to record up to 52 passes per day, by slightly tilting the antenna so that it pointed toward a spot 1100 km over the North Pole. The
system also had a second frequency of 150 MHz which allowed automatic compensation for ionospheric refraction.

Finally, at the end of the summer melt of 1967, when flights to T-3’s rebuilt ice runway resumed, we received the equipment to compute the fixes. It consisted of an ASR-33 teletypewriter and a power hungry (780 watts - 6% of T-3’s supply) Digital Equipment Corporation PDP-8/S with 4K of 12 bit word core memory and a 110 baud current loop teletype interface. Although the method today seems primitive, at that time it seemed to be space-age magic. Using the ASR-33, the majority voted ephemeris data and up to ten integrated Doppler counts were punched on to paper tape. Then an initiation code was entered manually into the flapper switches on the computer panel, telling the computer to begin reading a paper tape with the analysis program, written at Lamont’s Gravity department. Once this was loaded, the teletypewriter prompted for loading of the data tape, and then the computer’s panel lights began a dance lasting up to a half hour, followed hopefully by the teleprinter printing out the Latitude, Longitude, and Time of the fix.

A few fixes per day were processed this way on the station for immediate use, while the final track was determined back at Lamont when the ephemeris data and Doppler counts were punched on 80 column IBM cards for processing on the IBM 1130. Three to four Dopplers were enough for a fix. The fact that we knew the approximate course and speed of the ice, and could majority vote the ephemeris data (which could contain transmission errors), plus remove erroneous Doppler counts, meant that the final track was a smooth and curvilinear line followed by the 5 billion ton sheet of ice.

The installation of the Transit navigator coincided with the deployment of an array of several current meters down to depths of 295 m below the ice. The detailed navigation, together with the current speeds and directions at selected depths produced the first evidence of mesoscale eddies in the Arctic Ocean.

GPS - The Situation Now

The advent of the worldwide Global Positioning System (GPS) in the late 1980s completely altered the navigation situation in the Arctic, and is an important component in a new polar project we are undertaking (see below). But the accuracy and availability offered in the Arctic (and Antarctic) regions is diluted by the fact that the six orbital planes for the nominal 24 satellites in the system are inclined at 55° to the Equator, meaning that above 55° latitude there are no satellites overhead. Thus in the Arctic, while as many as 15 or 16 satellites may be visible, the satellite elevations rarely rise above 45 degrees and observed position dilution of precision (PDOP) may vary from a very respectable 1.5 to 2.0 as high as 5.5 with numerous short period spikes.

The GPS - the Situation Now

Figure 8: Testing of the geophysical instruments from the edge of an ice-flie. Here the components of the autonomous drifting seismic buoy are being tested. The craft has gear for shallow and deep seismic survey, as well as bottom sampling with camera, dredge and corer.

The platform for this project is a 13 m Griffon Hovercraft built by Griffon Hovercraft Ltd. (now Griffon Hoverworks Ltd.) in Southampton, England. The craft is named the R/H Sabvabaa, an Inupiaq name meaning ‘flows swiftly over it.’ The R/H is the first use of the designation Research Hovercraft. The craft is powered by a 440 hp Deutz water-cooled diesel engine, 40% of whose power is to produce the hover, with 60% powering a 2 m diameter ducted controllable pitch propeller. During the sea trials in the Solent the craft exceeded 43 kts, 8 kts over its design speed.

The Sabvabaa is equipped to carry out marine geophysical, geological, and oceanographic measurements from above the thick multiyear ice in one of the most inaccessible parts of the Arctic. Since June 2008 the R/H Sabvabaa (http://www.polarhovercraft.no) has been based in Longyearbyen, Svalbard at 78°-14’N. The summers of 2008 and 2009 have seen some 12,000 km of travel while undergoing sea and ice trials, and development and testing of a suite of specialized light-weight equipment for carrying out seismic profiling, bathymetry, and seafloor sampling. The hovercraft weighs approximately 5 tons. Although its payload is officially 2200 kg, several of the nine forays to the Yermak Plateau have seen payloads of almost 3500 kg. The maximum clearance on hover is 73 cm, meaning that the craft must avoid areas of rubble ice and the long sinuous pressure ridges which form when ice floes collide under compression.

For navigation, the hovercraft is equipped with a Furuno VX2 GD-1920C Color Video Plotter with NavNet vx2 Ethernet connectivity to the radar, flux-gate heading sensor, and a GPS/WAAS capable of tracking 12 satellites. The Furuno's GPS information,
downloadable on an SD memory stick, is also immediately available on a Gigabit LAN that serves up to 8 laptops and data acquisition devices. In addition the hovercraft carries several small Garmin GPS-18x USB receiver modules for additional navigation input to other computers.

From the perhaps 8% of the Arctic Ocean mapped thus far by aircraft landings, ice stations, ice breakers, and nuclear submarines, we have a rough idea of the ocean’s bottom topography (see Fig. 1). In order to study features of interest, it is likely that we will often use GPS to determine the immediate ice drift (varying from an average of 5 km/day to up to 20 km/day). We will then travel up-drift and settle on a floe from which we can make seismic profiles across these features, as well as sampling the bottom at will with corer, dredge, and camera using a portable winch with 3500 m of Kevlar rope and a capstan (Figs. 8 & 9).

GPS also plays a pivotal role in the development of autonomous drifting seismic and echo-sounding buoys which we intend to deploy from the hovercraft (Hall, 2006). The seismic buoy uses a methanol fuel cell to power a capacitor bank which produces an underwater spark every 50 m of travel as determined by the GPS. A hydrophone picks up the sub-bottom reflections from as much as a kilometer below the seafloor, which are then sent as a digital Short Burst Data message to Norway via an Iridium satellite telephone. Stacking these arrivals produces a low-cost seismic profile. The echo-sounding buoy uses a 3.5 kHz transducer to obtain depths every 20 m of drift, with the depths and positions again sent to Norway at various intervals. In future we envisage a capability of even doing shallow CHIRP seismic profiling using bi-directional Iridium messages for changing the data acquisition program.

Looking back at the capabilities of polar navigation just 20 years ago, it is clear that little of the present hovercraft program would be possible without the subsequent maturing and miniaturisation of GPS.

References

Figure 9: Our operating area is off the map (here the northern part of the Svalbard archipelago). A screen shot of the Furuno navigation plotter. Note the 25.6 kt speed over the ground (SOG), which is the hovercraft’s ‘sweet spot’ over water.