A Geologist-Oceanographer's-eye-view of changes in Marine and Land Positioning Capabilities, ca. 1930 – 2006

Abstract

In the early 1960's air navigation over the Arctic Ocean was by dead reckoning and celestial navigation, assisted by beacons on the drifting ice stations. Errors could amount to over 100 km even in good conditions, and so flights were not permitted when radio propagation conditions prevented the beacons on the ice stations from being heard. The best accuracies that could be achieved on the ocean surface, using a permanently mounted theodolite for celestial navigation, was about 1.0 nautical mile. Beneath the surface, submarines could be 30 n.mi. from their estimated position after 1000 miles of travel.

Re-location in the mid 1960's of drill-holes drilled in the 1930s in central Africa revealed positioning errors of about 300 feet. This probably arose from the fact that the original survey had been tied to an astronomically observed base station, since at the time the holes were drilled the nearest European settlement was more than 200 miles away. By the late 1980s early GPS was available, and isolated surveys could be accurately located without tying into distant triangulated networks.

Early (1984) satellite images of the ocean could be as much as 30 km from their reported positions. At present, satellite images of the sea surface are so accurately positioned using orbital and attitude data that features can be mapped at scales of up to 1:50,000 without the need for any tie to a surveyed-in feature, which is useful indeed when one is mapping features several hundred miles off-shore.

Introduction

In the 40-odd years that I have been a geologist and sometime oceanographer I have witnessed amazing changes in the way we have measured the positions of things. Geologists and Oceanographers are not really surveyors, but we are, in a very fundamental way, mapmakers. We are rarely concerned with the position of a boundary monument to the nearest 0.01 foot, but all geologists are (or, perhaps, were) trained to use a plane table and alidade for field mapping, and many of us have had occasion to use a theodolite, a dumpy level, or a tacheometer during our careers. Similarly, many oceanographers have used a sextant to observe the stars and the Nautical Almanac to work up fixes. However, I must be one of relatively few people who have used a theodolite to navigate at sea, and I am now one of a few people who routinely rely on the accurate positioning of satellite images to make maps of marine features far off-shore – in my case, oil slicks. In between I have had some interesting times relocating diamond drill-holes in the African bush and was a witness to some very early uses of GPS.

Navigation and Surveying, Ice Station T-3, 1963

In the summer of 1963 I was the junior scientific member of the crew of drifting Ice Station T-3 (aka Fletcher's Ice Island and Ice Station Bravo), which was then located around 83°N and 155°W. To get there we flew for 5 hours due north across the ice from Point Barrow in the Arctic Research Laboratory's ancient R4D (the Navy name for a DC-3). The rear door was held shut by baling wire, and we huddled in the icy hold in full Arctic gear. As we approached the station the scatter of tiny buildings looked like a cluster of dirty packing crates thrown down onto the endless expanse of ice

The first sight to greet us as we ground to a halt in the impressive cloud of snow and ice chips thrown up by our props was the skeleton of a dead R4D lying with its nose buried in a snow drift (**Fig.1**). My impression that this camp **(Fig.2)** might be a fragile home for the next four months was strengthened.

This impression had been created by the hair-raising tales of the events of the previous couple of years on T-3 that I had been told in Point Barrow. Alistair MacLean wove these events into the plot of his thriller "Ice Station Zebra", later to become Howard Hughes' favorite movie. The explosion and fire that killed several people after a visit from an icebreaker, the visit by an American submarine **(Fig.3)** and that by Russian scientists had all happened within a period of eighteen months in 1960-1962.

I had to wait several days at Barrow for radio conditions to improve enough to undertake the 700-mile flight to T-3. The DC-3 was not allowed to leave on its supply flight to T-3 and ARLIS-2 until the pilot could clearly pick up T-3's radio beacon, since that was the only navigation aid that he had. LORAN existed, but was confined to the "civilized" world down south.

1963 was supposed to be a year with few sunspots. As such, preparations were already well advanced for the International Quiet Sun Years (IQSY - Jan. 1, 1964, to Dec. 31, 1965), which were to begin within 7 months. During this period surrounding the solar minimum, solar and geophysical phenomena were studied by observatories around the world and by spacecraft in a major international co-operative effort to improve our understanding of solar-terrestrial relations. However, the reality of the summer of 1963 was different, and affected our lives severely!

The aurora belts surround each magnetic pole like doughnuts, and represent the zones in which the Van Allen radiation belts intersect earth's surface **(Fig. 4).** Point Barrow is on the southern edge of the belt, but T-3 and ARLIS-2 were in the doughnut hole **(Fig. 4).** Sunspots eject vast quantities of charged particles, which interact with Earth's magnetic field and give rise to beautiful displays of the Aurora. However, at these times radio waves traveling north tend get trapped in the Aurora Belt and travel around the Van Allen Belt to the opposite hemisphere. The Van Allen belts are a result of the collision of Earth's magnetic field with the solar wind. Radiation from the solar wind then becomes trapped within the magnetosphere. The trapped particles are repelled from regions of stronger magnetic field, where field lines converge. This causes the particle to bounce back and forth along magnetic lines of force between the earth's poles **(Fig.4),** where the magnetic field increases. There were long periods of time on T-3 when I could not receive the time signal from WWV in Alexandra, VA, or any of the other northern hemisphere stations. However, during those times I could listen to the BBC broadcasting to the Falklands, Radio Moscow broadcasting to Africa, and Radio Johannesburg.

Without radio beacons, the only means of navigation were dead reckoning and astronomical observations. Dead reckoning didn't work so well, since so close to the North Magnetic Pole the compass was not reliable. So the co-pilot used a sextant to shoot the sun, if he could see it, and plotted the resulting lines on the navigation chart in the cabin. In winter-time he could use the stars and actually get a fix, but in summer there was only the sun, and the airplane would move perhaps 50 to 60 miles between sun shots, making navigation an artistic mixture of hurried science and inspired art, since a "fix" was impossible. It would take 5 to 10 minutes to plot a single sun line: you had to look up the ephemeris data in two different places in the almanac, do a series of calculations to obtain the solar azimuth, and then physically plot the line on a map. There were no pocket calculators then! Not only did the aircraft's speed make it impossible to get a fix, at this latitude the sun's trajectory through the sky is so flat in summer that our change in latitude between shots was greater than the sun's change in elevation! Not to mention the fact that the sun could disappear behind the ever-present clouds at any time. Thus the requirement that the radio beacon be audible before we even left Point Barrow.

Ice Station T-3 was not the only American station manned that year: ARLIS-2 (Arctic Research Lab Ice Station 2) was near latitude 88°N, within a hundred miles of the North Pole and 350 miles North of T-3. Whereas we had eight people and were 700 miles from the nearest habitation, they had 5 people and were 1000 miles from people. Early in the summer, Jay Hirschman on ARLIS seemed to catch the flu, then pneumonia. No aircraft could land on the melted out runway of either ice station, and there was nothing the doctors could do, over our weak and intermittent radio links, to save him. Sunspots meant not just poor navigation, but total inability to communicate with the rest of the northern hemisphere. The crew of ARLIS was soon down to four people and a body in the freezer, along with their meat supply.

It took several weeks, including days in Barrow waiting for reception of T-3's radio beacon, to get a C-130 up from Phoenix to lift the body off, and then the first attempt failed. With the C-130 at the limit of its range, there was no opportunity for a second attempt. It was several more weeks before the plane came back and made a successful attempt: they dropped a balloon, which the crew on the ground attached to the body and then inflated. The plane made another pass, caught the wire attached to the balloon and winched the body aboard **(Fig. 5).** The system was known, after its inventor, as the Fulton sky-hook. The news came back from the Lower 48 that it had not been pneumonia at all, but a rare form of cancer of the heart, that had killed Jay.

These problems meant that we also ran out of food and, perhaps more importantly, tobacco and alcohol. We were supposed to receive paradrops from an Alaska Air

National Guard DC-4 about once a month, but by the time clear communications with Barrow allowed them to come out, they were more than a month late. We had run out of meat and vegetables, and our staples had become oatmeal porridge and cans of baked beans left over from the International Geophysical Year (IGY) of 1957-1958. These had been left in a cache near camp, but the polar bears had discovered them, and most had been neatly ripped open and devoured. The bear put a claw through each end of the can and simply twisted and supped. I've known a couple of old Aussie prospectors who could almost do the same with a can of Irish stew! The beans in the cans that were left intact had turned hard and black around the outside of the can, and were not too appetizing!

An illustration of how difficult navigation could be at that time and place was the case of the Norwegian pilot who hoped to make the first solo flight across the pole from mainland Norway to Barrow, supported in part by the National Geographic. He was supposed to pick up ARLIS-2's beacon, lay off a bearing that would take him over the North Pole, cross over ARLIS, and then pick up our beacon and cruise on over us to Barrow. ARLIS never saw him, but we did. He must have missed the North Pole by well over a hundred miles **(Fig.6)**, in perfect sunny weather.

Things were little better on and below the ice. My jobs included reading the gravity meter, the magnetometer, and the Precision Depth Recorder (PDR), in addition to running a third-order weather station and "navigating" the Island. This latter was what made map-making possible, and was thus the key to all else, and was done more accurately than the DC-3 navigator could do, but using the same techniques.

Now T-3 was not your normal ice floe – it was actually a 50m-thick tabular iceberg of the type that we usually think of in connection with the Antarctic, and measured 69 square miles in area the summer that I was there. It broke off from an ice shelf attached to Ellesmere Island, in the Canadian Arctic, perhaps 80 years ago, and had been carried around the Canada Basin of the Arctic Ocean a couple of times since then by wind and current **(Fig.6)**. Its path was an intricate squiggle that crossed and recrossed itself – Figure 6 cannot really do justice to how squiggly. When we crossed on of our old tracks, we could use the Precision Depth Recorder (PDR) charts to adjust our position by making sure that the depth on each leg was the same at the crossing point. The only trouble was that a lot of the time we were over the Canada Abyssal Plain, which was exactly 3870 m deep for hundreds of miles.

Not only did the island wander around, but it spun on its axis when leads opened up or floes were driven against its corners. One day the sun went around backwards 3 times – we were in relatively open water and had been set spinning clockwise much faster than the sun. VERY disorienting! Even internally, T-3 was not a static object: every summer, about 3 feet of ice melted, carving the surface into a rugged and slippery topography characterized by slot-like canyons 6 feet deep which carried the melt water to the ocean **(Fig.7**). Not only could nobody land on the island: we residents could not safely move more than a few hundred yards from camp, through the whole period of melt. We could stumble through the jumble of slush and water at about two miles per hour, but a polar bear, invisible from more than a few yards away, could move at 30 miles per hour. One had been shot walking through the camp the previous year, and its skeletal, massive but very human (the claws had been nibbled off by later ursine visitors!), hand melted from the snowdrifts during my first couple of weeks on-ice. Every winter, three feet of ice froze to the bottom of the berg, replacing the ice lost from the surface and often trapping a small herring or two. Fifty years later these herring would melt out of the surface! They had been carried completely through the 150-foot thick berg by the melting and freezing process, along with the very ice that surrounded them and composed the iceberg. T-3 maintained a constant thickness of 50 m, but none of its ice was more than 50 years old, in spite of the fact that it had broken from an ice shelf thousands of years old, and the ice island itself had been in existence more than 50 years.

In order to navigate accurately we had a Wild T-2 theodolite set up on a12x12 post that was sunk perhaps ten feet into the ice. We stopped the theodolite post melting out of the ice during the summer by surrounding its base with tarps and old parachutes, preventing the sun and the warm air from reaching the ice. Very soon the theodolite post stuck out of a tiny plateau on the summit of a steep little hill of ice **(Fig.8**). By the time I got there, this hill was in its second season and over six feet high. Since the theodolite was kept in the warmth of the wanigan (trailer) when not in use, this meant stumbling up the slope with one arm full of instrument and the other of notebooks and pencil every time I took a reading, generally three times a day.

Back at Columbia University, my job as a graduate student was to plot up our data on the bottom topography, the gravity and magnetic fields, and so on. Since all the navigation data had been calculated by hand, the most tedious job was re-checking and re-plotting years' worth of data. Because our theodolite was fixed to a stable platform and could be read to a few seconds of arc, we were able to locate our position orders of magnitude more accurately than any of the heroic Arctic expeditions. The greatest obvious limit on our precision was that the Almanac only gave various quantities to the nearest tenth of a minute, which translates to 0.1 nautical miles on the ground. However, the sizes of our triangles of error, when we plotted all three shots to get a fix, suggested that our average precision was perhaps about 1.0 nautical mile. Atmospheric refraction was a major factor in this, and perhaps the drift of our watches between checks from WWV: a one second time error equates to a 0.25 nautical miles positional error, all other things being equal. There was no independent way of checking our accuracy.

As part of making the bathymetric chart of the Canada Basin, I obtained the continuous depth recording that had been made by the USS Nautilus on her historic "under the pole" voyage. T-3 had wandered around over and near Nautilus' track for more than a year **(Fig.6**), and so we were able to make a pretty good map of the area, which fortunately lay in steep topography over the southern flank of the Alpha Rise**.** The only way that I could make the Nautilus' depth recordings fit our map was to move their track 30 miles away from the North Pole. Inquiries of the Navy confirmed that, at the time, that was about the best that could be expected from their inertial navigation systems.

Relocating old Drill Holes, Nkana Syncline, Zambia, 1966:

During the 1960s and 1970s the Central African Copperbelt was the second largest producer of copper in the world, with two-thirds of its production being from Zambia. The original exploration had been done in the 1920s and 30s, and the mines opened on the eve of World War II. When they were opened, the near-surface, oxidized ores were not economically treatable, but by 1966 they were. I was assigned to re-map the west limb of the Nkana Syncline, which had been pitted and drilled in the 1930s and then abandoned.

In Zambia there is no outcrop. In order to map the geology it was necessary to hire a crew of laborers who dug circular pits, less than 2'3" in diameter, down to the weathered bedrock **(Fig. 9).** The pits were sometimes 60 feet or more deep. The geologist then descended the pits on a 15"-long piece of 2"x10" knotted to the end of a long rope. By the light of a miner's headlamp he recorded the lithology and the attitude of the rock, and marked off intervals for sampling. Near the bottom you had to be aware of any trapped snakes, and every once in a while a pit would be filled with poisonous gas. If we encountered minerization, we would connect adjacent pits with a tunnel or cross-cut **(Fig.10)** in order to get a representative sample across the width of the Ore formation. These cross-cuts were about 2 feet wide and 3 feet high, and I had to wriggle through on my side.

The pits were 50 feet apart in lines 500 feet apart. We usually were able to inveigle a mine surveyor into cutting and marking a baseline for us, but we laid out the pit-lines using antique theodolites, and marked the pit locations using a 200-foot chain. Apart from dense brush in places, the main problem we faced was the ant-hills **(Fig. 11),** huge termite mounds 50 feet across the base and up to 17 feet high: we were continually offsetting lines around them, and it was from them that poisonous gas seeped into the pits.

In this particular area there were about eight drill-holes. I wanted to find them for two reasons: I had logs and could incorporate them into my cross-sections if I knew exactly where they were, and there was also the possibility that there would be a "core graveyard" at the site, and that would give me a chance to resample and re-describe the core. However, extensive searching around the reported positions yielded nothing. One hole had been 2265 feet deep and had taken 16 months to drill with a steam rig in 1931. Surely we could find it! Well, we did, not only the hole, but most of the rig (based on an old steam tractor) rusting away, and all of the core, neatly lined up and labeled. But it was over 300 feet from where it was supposed to be, in rather thick bush, which hid everything until you walked into it or tripped over it.

The only reason for the large positional error that I can think of is that the original mine grant surveys of the 1920s were tied to a local origin that had been located by astronomical observations long before the road and the railway ever got up here. At that time the nearest European settlement was more than 200 miles away. The first order triangulation would have arrived with the railway in the later 1930s. Probably it was worth no-one's while to tie remote areas like the West Limb back to the new, accurate, datum. I know that the Zaire-Zambia Border demarcation was done two decades after those holes were drilled, and assume that lack of a first order triangulation was one of the reasons for the delay. Based on my Arctic experience, a 300-foot (0.05 nautical miles) error would be pretty good for an independent astronomical datum, and must have represented a fairly long series of observations.

Early GPS, Papua-New Guinea, early 1989:

We were out on a seismic survey in the Fly River jungles and, as it had been in Zambia in the 1920s, the problem was tying our work to some absolute datum. Our Party Chief, Floyd Doty, was an "early adopter" and had brought out a GPS receiver. This TI-4100 **(Fig.12**), cost $140,000 and was huge, weighing about 80 pounds. It also needed two 12V car batteries to power it. It could track only 5 GPS satellites, using a multiplexing technology, but at this time there were only 4 or 5 operational GPS satellites available. The box was not sealed off from the steamy jungle atmosphere, and Floyd found that it grew enough mold to stop it operating in about two days. He spent large amounts of time partially dismantling and thoroughly cleaning it. It could hardly be called a mobile receiver, but I think it made it to the beginning and end of every line, partly by chopper and partly on human backs.

What made things much worse for Floyd was that he was the only person who knew how to work it, and the satellites all seemed to pass overhead in the small hours of the night. So Floyd wasn't getting much sleep. But he did get the job done.

Natural Oil Slicks, 1987 –2006

In many areas of the world, oil seeps out naturally from the bedrock onto the sea floor. From there it rises up in bubbles to the sea surface to form oil slicks that can be very extensive. The most famous such areas are at Coal Oil Point, near Santa Barbara, CA., in the Gulf of Mexico **(Fig.13),** and in the Caspian Sea. Oceanographers at Texas A&M estimate that 100,000 barrels of oil seeps into the Gulf of Mexico each year: there are days when the surface of the Gulf is one giant slick for as far as the eye can see, and it has been like that since at least the 18th century, when a Spanish captain reported sailing through oil for three days.

In the mid 1980s it was realized that these slicks could be seen on Radar images of the ocean captured by a short-lived satellite called SeaSat, and also on visible images from the new Landsat 4 satellite. It was also realized that, if a basin was seeping, it had an oil charge, probably in abundance, whereas, if it wasn't seeping it perhaps didn't contain oil.

People therefore started looking for these slicks all over the world on Landsat TM data, and later on satellite synthetic aperture radar (SAR) data **(Fig.14)**. Often there is no land at all on these scenes, so we have to believe that they were where the space agencies say they are. In the early days of Landsat 4 we had a few cases in Asia in which there was land on an image, and it became quickly apparent that the images could be mislocated by as much as 30 km. This situation arose because NASA could only recalibrate ("upload" in their terminology) the satellite orbit when it passed over their tracking station in Wallops Island, VA. Landsat 4 had been designed to broadcast its data to the DoD's TDRSS (Tracking and data Relay Satellite System) satellites. This was a system of three satellites in geostationary orbit, equally spaced around the equator at 120-degree intervals so as to have the whole earth in view. Data could be sent up from anywhere on earth to nearest TDRSS, which then passed it to the TDRSS that had the destination in view. The latter downloaded it to the user. The loss of the second TDRSS satellite on launch, and the resulting delay in launching the third, left a whole part of the world "dark" to NASA and DoD communications. Since it could be a week or more between successive Landsat transits within range of Wallops Island, orbital drift thus became a serious problem.

Nowadays satellite tracking is routinely so accurate that, with a little bit of work, orbits can be located to the nearest 10 m, and so we never have to worry about the locations of our images when observing the ocean. Thus topography can be mapped, and earth movements monitored, by Radar Interferometry, which compares the distance from the satellite position at two different dates to a point on the surface and can detect movement of as little as 0.5 cm of that point between satellite passes (**Fig.15??**). Positioning is so good at sea, that the changing positions of oil slicks on images of different dates can be used to measure subsurface currents that have deflected the column of oil bubbles on its ascent from the sea floor.

Navigating on or above the water, anywhere in the world, GPS can always locate us to within a meter or ten, depending on the effort we are willing to go to. Under water, inertial guidance systems are also orders of magnitude more reliable than they were, but we have also mapped the bottoms of all the oceans in such detail that it is possible to use swath or wide-beam sonar to locate oneself exactly in relation to known features of the sea floor **(Fig.16??).** Even a submarine in "quiet" mode has full-tensor gravimeters aboard which can warn it of topographic obstacles ahead.

The world is definitely a less mysterious place in terms of our knowledge of where we are upon or above its surface, and that may in some respects be a loss. However, it is only this accuracy that makes it possible to develop and use techniques like 4-D seismic. With this technique we can measure the depletion of oil reservoirs in real time because of the changes it causes in sound-wave reflection. However, it requires regular re-surveys of the area, and each time the vessel must follow *exactly* the same course as it has on the previous surveys, and the shots and receivers must be in the exact same positions: in other words, the geometry of data acquisition has to be identical each time. It is this same positioning accuracy that enables us to re-enter drill-holes in 10,000 feet of water, and it is only this level of accuracy that gives our cars the uncanny ability, once possessed by some horses and donkeys, to bring us home when we don't know the way.

LIST OF ILLUSTRATIONS:

Figure 1: The downed R4D on T-3, photographed in 1961 (courtesy web-site kf3-aa)

Figure 2: The Mess Hall at T-3 in 1961. This building burned down with a loss of life in 1962 after fuel pumped from the bilges of visiting icebreaker Northwind was used in the furnace. The fuel contained seawater, which put the furnace out, but the burner remained hot enough to explosively ignite the next "slug" of fuel to reach it. (Courtesy web-site kf3aa)

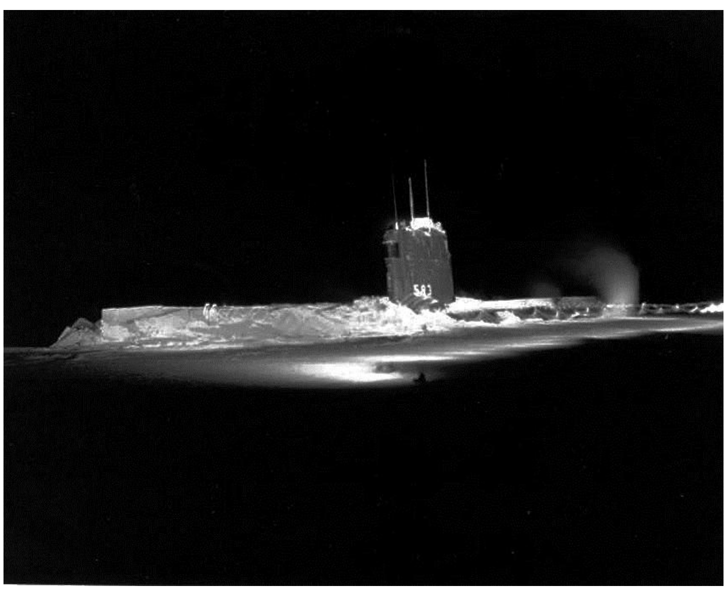

Figure 3: USS Sargo at Ice Station T-3, 1960 (Courtesy of USS Sargo web-site)

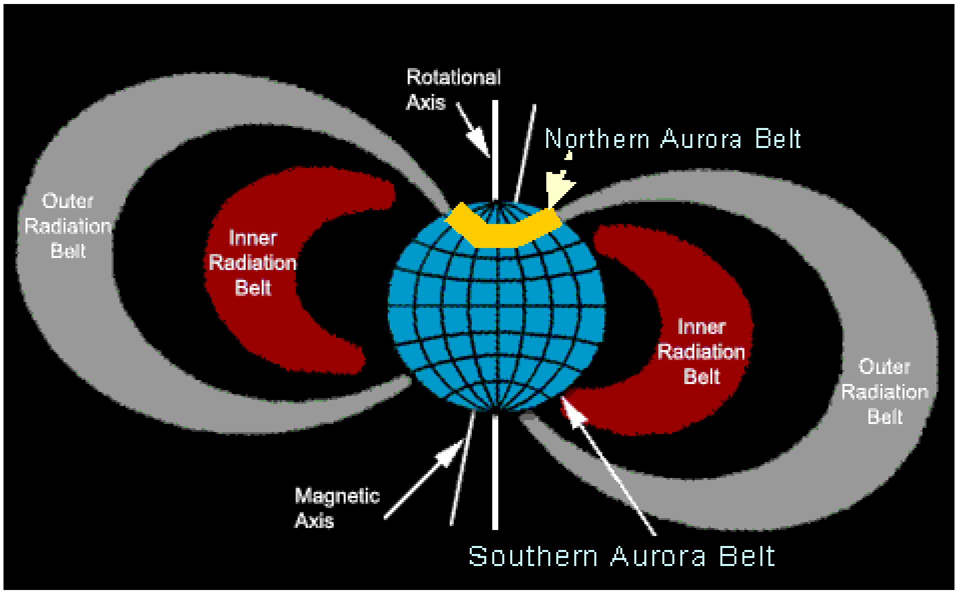

Figure 4: The Van Allen and Aurora belts. The Van Allen belts follow magnetic lines of force between the two magnetic poles, and the aurora belts occur where they encounter the earth's atmosphere in a doughnut shape around the poles. Radio signals cannot cross the belts directly during auroral (sunspot) activity, but are "caught" in the Van Allen belt and received in the polar regions of the opposite hemisphere (modified from a drawing in Wikipedia)

Figure 5: The Fulton "Sky Hook" system in operation. The aircraft catches the balloon cable with the Y-antenna at its nose, and the person being rescued is then winched into the cargo hold. In this photo the balloon appears to be just above the top edge of the photo (Courtesy C130 Sky Hook web site)

Figure 5a: The DC-4 on its way out to ARLIS-2, showing the antenna for the Fulton "Sky Hook" system at its nose.

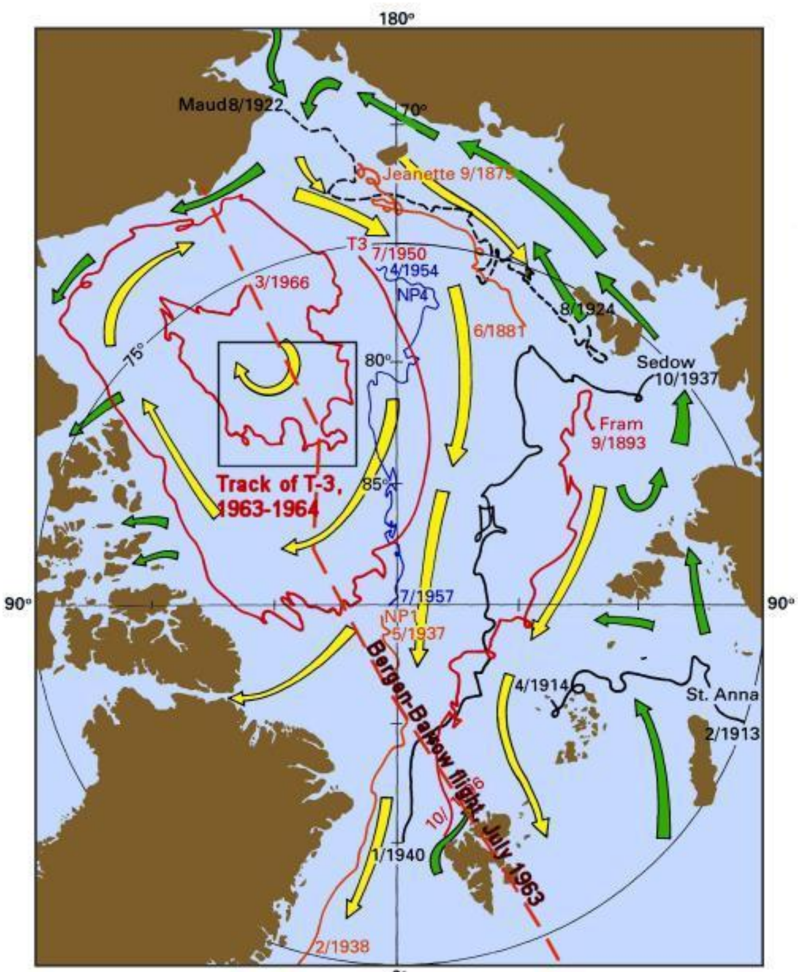

Figure 6: Currents and Ice Station drift tracks in the Arctic Ocean. T-3's track is the continuous red line: the part enclosed in a box is the track from early 1963 to late 1964. ARLIS-2 followed roughly

the blue track of NP-4 during 1962-1963, and then went across the pole and down the east Greenland current in 1964 along the track followed by NP-1 in 1937-8. The large yellow and green arrows show the general circulation of the ocean water. (Courtesy Flinders University website)

Figure 7: Meltwater channel and generator shack on Ice Station T-3, September 1963, after the freeze had begun (photo by JLBerry).

Figure 8: The theodolite post and weather "beehives" at Ice Station T-3, September 1963. The blowing snow in the foreground is due to increasing wind, which later became a blizzard (JLBerry)

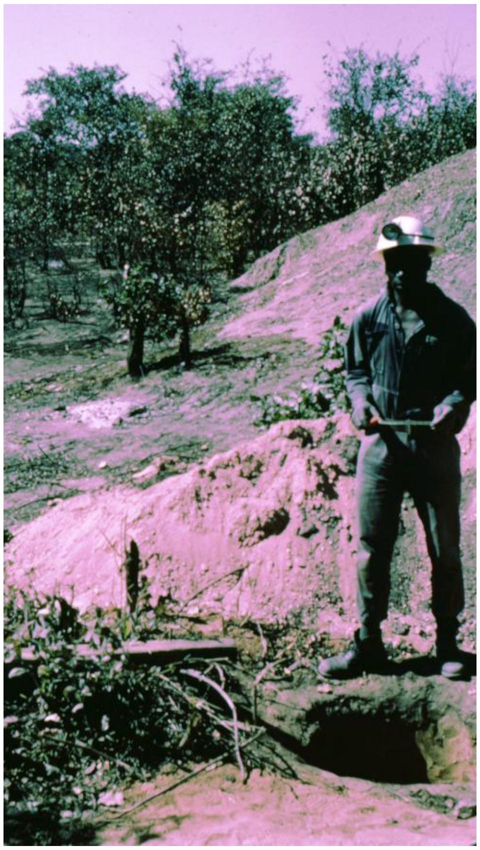

Figure 9: Prospect pit at Nkana, Zambia, 1968. The geologist has logged the pit and marked out sample intervals in his notebook. This sampler will go down the pit on a rope and sample according to the geologist's instructions (JLBerry).

Figure 10: Cross-cut at Nkana, Zambia, 1968. The tunnel is 2' wide, 3'high, and 25' long. The tape pegged to the wall enables the geologist to describe the rocks and locate their contacts. The sampler, in the distance, will follow the geologist, cutting a channel sample along the tape(JLBerry).

Figure 11: Two "ant hills", or termite mounds, Nkana, Zambia, 1967. The one on the left is older and larger, perhaps 15' high. The one on the right is younger and still has a central sharp spike. (JLBerry)

Figure 12: TI-4100 GPS receiver, used in the late 1980s. This box weighed ~80lbs and could track 5 satellites. (Courtesy GPS history website)