SATELLITE GPS MEASUREMENTS OF LANDFAST ICE DISPLACEMENTS IN THE CANADIAN BEAUFORT DURING THE WINTER OF 2003

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ABSTRACT

Three GPS (Global Positioning System) beacons were placed on the landfast ice cover of the Southeastern Beaufort Sea in mid-February, 2003. Changes in the positions of these beacons, roughly 35 km offshore of Richards Island and the Tuktoyaktuk Peninsula, were deduced from data relayed through the System Argos satellite network.This data acquisition program was carried out for Devon Canada for input to a planned drilling program. Position data with sufficient continuity from two of the three beacons were used to document landfast ice movements at both the western and eastern ends of the area of interest. Consistent, but less detailed data, were acquired at the third, central, beacon site. The results showed capabilities forresolving movements with as small as 2m in both the north-south and east-west directions on time scales of 6 to 12 hours. All detected movements were limited to a period in March and involved a single primarily southward, ice displacement event, approximately 10 m in magnitude. Smaller (2-5m) eastward components of this displacement dissipated over a, roughly, week-long period immediately following the event. Satellite imagery and ice velocity data from mobile, more offshore, pack ice, allowed identification of the causal source of the displacements.

INTRODUCTION

The ice cover of the Beaufort Sea is characterized by an extensive zone of landfast ice adjacent to the Canadian and Alaskan coasts. This ice stabilizes in the early winter months with cessation of large scale ice drift on the inner continental shelf. This stability persists, usually, until early June when annual break-up dissipates the ice through melt and it moves offshore. In February 2003, a study was initiated by Devon Canada to quantify landfast ice movements for their planned drilling activities in Canadian waters just east of Mackenzie Bay.

METHODOLOGY

Basic Approach

This study was based upon extracting ice displacements from satellite-relays of GPS-position data acquired by ice beacons deployed by helicopter at three offshore locations of interest (Figure 1). GPS data were also gathered at a shore station in Tuktoyaktuk to investigate possible enhancements in displacement sensitivity/accuracy attainable with differential mode operations which measured ice positions relative to a a stationary GPS receiver reference. ClearSat Argos/GPS Marker Buoys manufactured by Clearwater Instrumentation of Watertown, Mass were utilized as the offshore beacons, employing a GPS engine and an off-the-shelf processing chip capable of providing position resolution to 0.0001 degrees in both latitude and longitude. Positions acquired at individual beacons were to be acquired at half-hour intervals and transmitted to the System Argos data collection and relay facility. The stationary GPS unit was comprised of a Pentax-Pro DGPS digital GPS platform located in a heated, indoor, Tuktoyaktuk location. The obtained Land station positions and auxiliary data were logged into a Toshiba 4010 laptop computer at 60Hz and with a higher (.00000017º) spatial resolution.

Unfortunately, the one month time interval period between project startup and deployment precluded careful testing of beacon functions prior to deployment .This had two major impacts upon the study:

1. Blank-out periods (intervals associated with missing half-hour position data) were ubiquitous for one beacon, forcing heavy reliance on data from the extreme eastern and western beacons. (Data recovery percentages were 87%, 24% and 77% for beacons 26361, 26436 and 26938, respectively.)
2. Permanent shut-off dates and times (to avoid incurring costs data transmission costs from the post-break-up period) were incorrectly preprogrammed into the beacons by the manufacturer, initiating shut-off on April7, 2003 instead of June 30, 2003 (Table 1).

Accuracy Issues

The intrinsic limitation of acquired beacon data collection capabilities to 4 decimal degree accuracy restricted measurements to a spatial resolution of about 11m and 4 m in, respectively, the north-south (latitude) and east-west (longitude) directions). Averaging of larger numbers of individual time series measurements allows further improvements in resolution, albeit with reduced time resolution. For random standard deviations of Δ_{lat} and Δ_{long} degrees in the two basic geographic directions, measurements at the planned half-hourly intervals should have, in principle, allowed estimates of daily (24-hour), and 4 times-daily (6-hour) mean positions with respective precisions of: $0.28\Delta_{lat}$ and $0.28\Delta_{long}$

degrees; and 0.56Δ_{lat} and 0.56Δ_{long} degrees to 95% levels of certainty. Unfortunately, gaps in coverage kept absolute position measurement accuracy at somewhat lower levels at all sites and throughout the planned monitoring period.

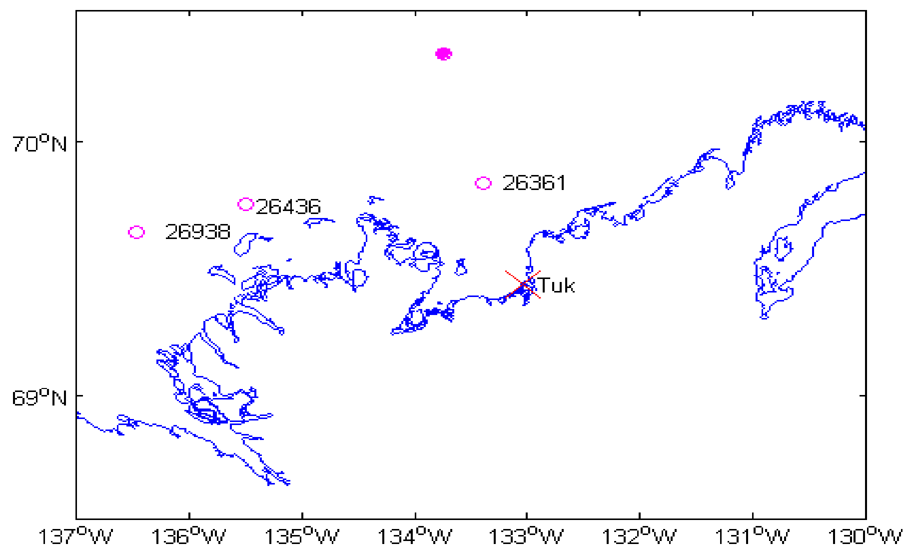


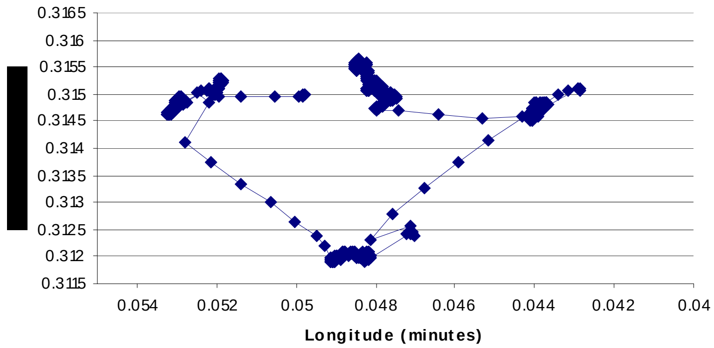
Figure 1. Beacon deployment sites and the location of the Tuktoyaktuk Land Station GPS site. The filled marker denotes the site associated with concurrent ice-velocity and -thickness measurements discussed in the text.

Beacon	**Latitude (° N)**	**Longitude (° W)**	**Activation time (MST), date (m/d/y)**	**First reported position time (GMT), date (m/d/y)**	**Last reported position time (GMT)/Date of last reported on-ice position**
26361	69.840	133.394	14:00, 02/19/03	22:15, 02/18/03 (? or 19th)	13:40, 04/07/03
26436	69.756	135.493	13:00, 02/20/03	16:33, 2/22/03	17:09, 04/07/03
26938	69.650	136.461	16:30, 02/20/03	21:31, 2/20/03	13:32, 04/07/03

Table 1. Ice beacon deployment details.

Two differential mode approaches were available for increasing sensitivity to displacements over shorter periods based upon computing each beacon position relative to either the fixed Tuktoyaktuk GPS unit or the other two ice beacons. Guidelines for such improvements were given by Prinsenberg et al. (1998) and by van der Baaren and Prinsenberg (2000) who suggested that standard deviations in the relative positions of adjacent stationary GPS beacons are very sensitive to similarity in the constellations of satellites used to establish individual beacon positions. In the absence of configuration data for our beacons, it was anticipated that near-simultaneity of measurement timing would best enhance prospects for all beacon positions being established with identical satellite configurations. Unfortunately, in our case, time clock differences and drifts rarely allowed position determinations to be made within the same +/- 100 s measurement window, precluding the likelihood that measurements of positions relative to adjacent beacons would increase displacement detection sensitivity.

Figure 2. Incremental (relative to nearest integral degree) positions of Sidney Land Station measured for sequential shifts to positions 5m east, 5m south, 5m west and 2m west of starting site.



Differential mode measurements were, in principle, feasible and Station reference since its 1Hz position data acquisition rate assured access to reference position data effectively coincident with all ice beacon position data points. On the other hand, the cancellation of measurement errors intrinsic to relative, equivalent, position measurements was unlikely to be obtained due to notable differences in the stability of ice beacon and Land Station data. Specifically, the standard deviations of the Land Station latitudes and longitudes as were approximately 2.1 $\times 10^{-5}$ ° (2.0 m) and 4.4$\times 10^{-5}$ ° (2.0 m), respectively, or, roughly, 2.5 times smaller than the corresponding typical ice beacon values, 5 $\times 10^{-5}$ ° (5 m) and 11 $\times 10^{-5}$ ° (5 m), precluding possibilities that subtraction of simultaneous Land Station positions from beacon positions would facilitate detection of beacon displacements. It was notable that the standard deviations of Land Station positions over the much shorter, typically, 30 s to 15 minute periods associated with constant numbers of satellites being available for position determination were 5 to 6 times smaller than those listed above for the Land Station data record as a whole. This is consistent with temporally variability in the satellite configurations being the principal source of Land Station measurement uncertainty. When translated into distance units, the shorter-term deviations characteristic of measurements with a given satellite configuration suggested that individual Land Station measurements (i.e. each measurement in the 1 s interval time series) had a 95% probability of being within +/- 0.65 m of the mean position along both the north-south (latitude) and east-west (longitude) directions. This expectation was confirmed in Sidney, B.C. tests (Figure 2)in which data were acquired at 1hz as the GPS receiver antenna was moved successively from an initial central reference position to positions 5m east , 5m south, 5m west and 2m west. The scatters of points around each stationary position were compatible with roughly +/- 0.5 m random errors in the EW and NS directions as well as the presence of larger random shifts in the centroids of the point clusters corresponding to measurements over periods long enough to allow changes in the available satellite configurations. The latter shifts were approximately equivalent to the 2 m positioning uncertainties attained in Tuktoyaktuk over equivalent time periods.

Questions remain as to the origins of the differences in the variability of the respective Land Station and ice beacon data sets. The persistence of elevated position variability in the best-performing beacon (26361) during a 17 hour period of immobility prior to deployment ruled out unresolved high frequency ice cover movements as the source of difficulties. Although the observations could also reflect quality differences between the beacon and Land Station receivers, the larger beacon position variations may be a consequence of round-off errors in the coarser resolution beacon output products.

RESULTS

General

These reviews of the data and the capabilities of the deployed beacons dictated that documenting ice cover movements as small as or even smaller than 2m required averaging multiple individual position estimates. Ideally, the 12 and 48 individual samples acquired with the planned sampling rate should have yielded 24-hour- and 6-hour-mean estimates of position within 95% certainty limits of 1.4m and 2.8m respectively in the north-south (latitude) and east-west (longitude), directions. In actual practice, breaks in sampling continuity, indicated in some data plots by separate identifications of interval-averaged points associated with smaller numbers of measured positions, often gave slightly larger uncertainties. All mean values were computed from data previously processed to effect removal of obvious outliers, first by automatic elimination of points deviating by more than 0.0002º and 0.00025º from 48 point running mean values and, then, by manual removal of points associated with anomalies in plots of means and variances

Absolute Position Time Series

Mean latitude and longitude values for the two of the three ice beacons with reasonable data returns are plotted in Figures 3- 4 and Figures 5-6, respectively, for successive, non-overlapping, 24- and 6- hour time intervals. In each case, latitudes and longitudes are presented for a given beacon along with corresponding brackets denoting the above-noted 95% certainty limits on a convenient, representative, data point. The 24-hour mean value data plots include data both as calculated for periods with more than 40 of the possible 48 included data points and for periods associated with smaller numbers of data points (>30 and >18 points for beacons 26361 and 26938, respectively). This use of data from periods of both greater and lesser data quantity enhanced the continuity of coverage and allowed examination of possible sensitivities to sampling completeness.

The most statistically-significant, 24-hour, results (Figures 3-4) suggest that the only truly unambiguous ice displacement detected during the studied period occurred on day 20 (March 11) at the most westerly (Figure 1) beacon (26938). The displacement event is most apparent in the latitude time series of Figure 4a which shows a sudden (within the 24 hour resolution of the plot) 0.00008° to 0.00009° decrease in latitude equivalent to a, roughly, 9 m southward shift with little evidence of either prior or subsequent north-south instability. A corresponding reduction in longitude, equivalent to something like a 4m to

5m eastward displacement is evident in Figure 4b. In the latter case, however, there is some evidence for both an earlier small (on the order of 2m) east-west instability as well as indications that the eastward displacement of day 20 slowly “relaxed” over the subsequent week, bringing the east-west position of beacon 26938 close to its immediately pre-day 20 value by day 28.

Equivalent reviews of the most complete 24-hour mean results for beacon 26361 showed somewhat less definitive evidence for smaller changes coincident with the beacon 26938 day 20 event. Such evidence is present only in the latitude data (Figure 3a) and, again, corresponds to a sudden decrease in latitude, equivalent to a, roughly, 1m to 2m southward ice shift. Moreover, as in the case of the beacon 26938 longitude results, the beacon north-south position then slowly returned over a period of about a week to a position equivalent to or even slightly north of its pre-shift location. The beacon 26361 longitude record (Figure 3b) shows no definitive signature of the day 20 event, short of a possible slight reduction (equivalent to a 1m eastward displacement) in mean longitudes associated, respectively with the pre- and post-day 20 periods.

The very sparse set of mean positions obtained for beacon 26436 (not shown) and the underlying small number (typically about 14) of actual measurements incorporated in the daily averages precluded definitive displacement event detection at this site. However, the pre- and post-day 20 latitude and longitude data show no evidence of differences comparable to those deduced from the beacon 26938 24-hour mean data. Corresponding (contemporary) 26436 site changes were unlikely to have exceeded 2 m in either the north-south or east-west directions.

The apparent regional motion trend indicated by the 24-hour mean results, namely a “permanent” mostly southward shift at the westernmost 26938 site along with smaller “impermanent” (relaxing back to a northward position) southward displacement at the easternmost (26361) site was not inconsistent with data obtained at the intermediate 26436 site. These results suggest that movements at the two more eastern beacon sites could be interpreted as weak responses to an ice cover shift which occurred near or to the west of the most strongly affected, westernmost, beacon 26361 monitoring site.
Similar conclusions could be drawn from the 6-hour mean positions plotted in Figures 5-6. Importantly, however, the noisier, higher temporal resolution, beacon 26938 results (Figures 6a,b) strongly suggest that the major displacement of day 20 took place on a time scale comparable to or shorter than the 6-hour averaging period and, probably during the first half of the time interval between 12:00 March 11 and 00:00 March 12. The suddenness of the displacement is evident in both the latitude and longitude results, with, again, the relative north-south (latitude) stability of the ice both prior to and after the displacement contrasting with the longitude results which showed evidence for net westward movement after the sudden shift. This movement essentially brought the beacon back to an east-west position identical to that occupied prior to the day 20 event. There is no definitive evidence on the shorter time scale for equivalent drift in the easternmost beacon (26361) data (Figure 5) although the results are not inconsistent with the slow northward relaxation of the smaller southward day 20 displacement and an equivalently slow subsequent net 1 m eastward drift inferred from the 24-hour mean

data. The magnitude of the sudden southward shift at this site can be seen to be on the order of 1 to 2m. The use of mean positions computed for periods shorter than 24 hours did not significantly clarify the sparse beacon 26436 results, confirming our previous judgment that displacements greater than the roughly +/-2m measurement uncertainties were not detected at this site.

Figure 3a. Plot of 24 hour mean latitudes for beacon 26361(40 or more data points only) vs. day (February 19 = day 0)[squared points denote means based on 30 < data points < 40] {each vertical division = 2m}.

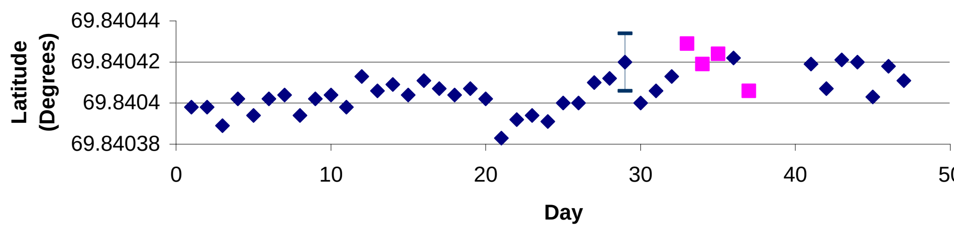


Figure 3b. Plot of 24 hour mean longitudes for beacon 26361 (40 or more data points only) vs. day (February 19 = day 0)[squared points denote means based on 30 < data points < 40] {each vertical division = 2m}.

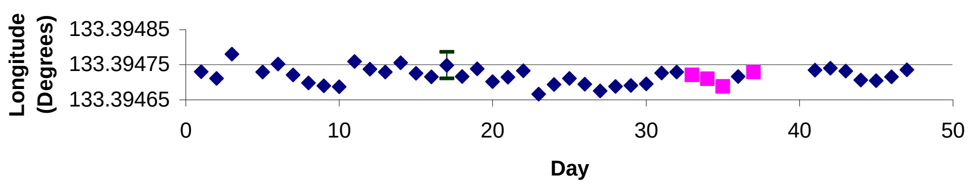


Figure 4a. Plot of 24 hour mean latitudes for beacon 26938(40 or more data points only) vs. day (February 19 = day 0)[squared points denote means based on 18 < data points < 40] {each vertical division = 2m}.

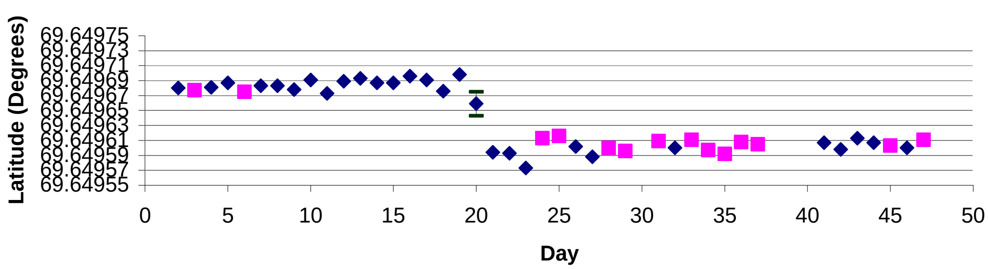


Figure 4b. Plot of 24 hour mean longitudes for beacon 26938(40 or more data points only) vs. day (February 19 = day 0)[squared points denote means based on 18 < data points < 40] {each vertical division = 2m}.

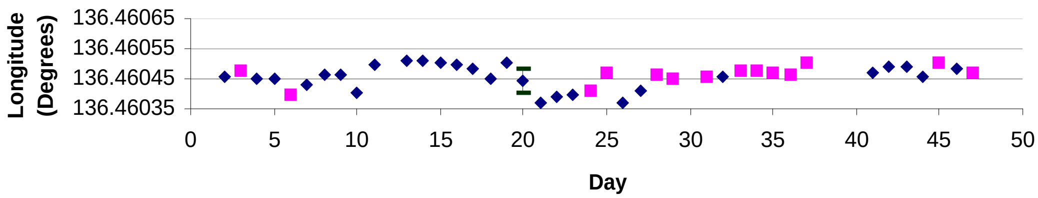


Figure 5a. Plot of 6-hour mean latitudes for beacon 26361(10 or more data points only) vs. day (February 19 = day 0) {each vertical division = 2m}.

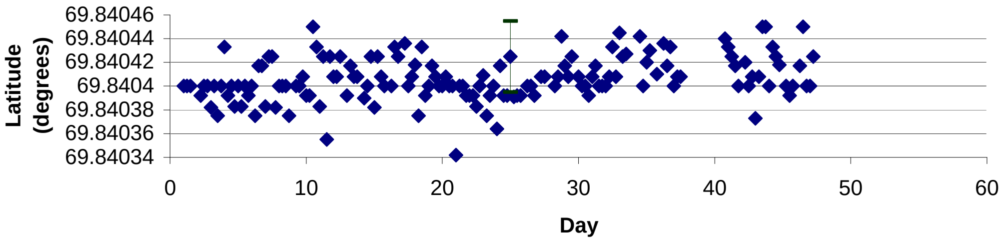


Figure 5b. Plot of 6-hour mean longitudes for beacon 26361(10 or more data points only) vs. day (February 19 = day 0) {each vertical division = 2m}.

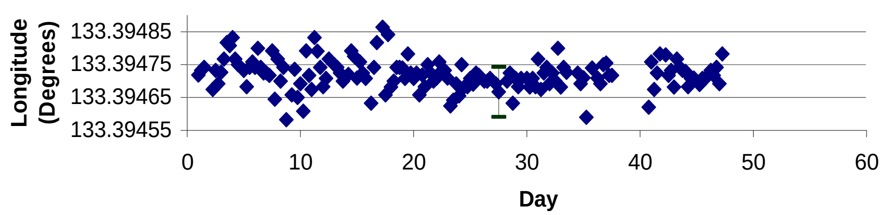


Figure 6a. Plot of mean 6-hour latitudes for beacon 26938 vs. day (February 19 = day 0). Data plotted for intervals with 6 or more data points {each vertical divison =2m}.

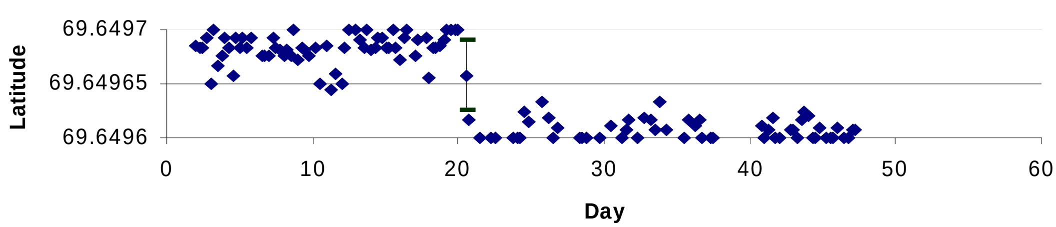
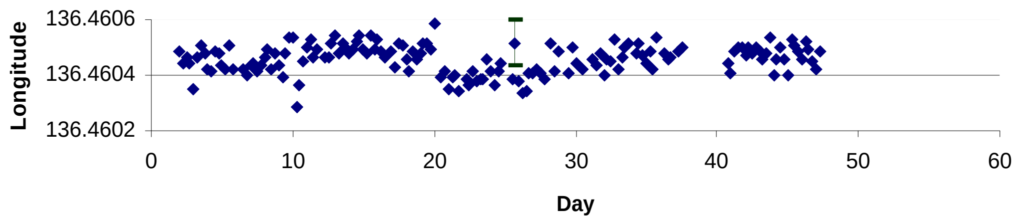


Figure 6b. Plot of mean 6-hour longitudes for beacon 26938 vs. day (February 19 = day 0). Data plotted for intervals with 6 or more data points {each vertical division =2m}.



DISCUSSION

Use of these results for planning and assessing future drilling programs requires relating the observed periods of landfast ice stability and ice displacement to larger scale regional processes as a first step toward developing prediction capabilities. Some progress in this regard was made using mobile ice drift data acquired concurrently by Dr. Humfrey Melling at a site (Figure 1) 55 km NNW of beacon 26361. Expressed in terms of cumulative northward and eastward displacements, these data suggested that an initial period (February 12-26) of negligible mobile ice movement was followed by extensive WNW drift which ended on March 5. Satellite imagery (Figure 7) show this drift created a region occupied primarily by open water and thin, new, ice at the outer edge of the regional fast ice zone. Three subsequent, March 5-6, March 8-10 and March 11-12, periods of shoreward movements (Figure 8) progressively deformed this ice, with the deformations in successively later periods occurring in ice of larger (deformed) ice thickness and, hence, requiring larger compressive stresses. The beacon displacement results suggest that the stresses transferred from the mobile pack ice only rose above those required for landfast ice failure and deformation during the March 11-12 interval and primarily at the westernmost (26938) beacon site. The significantly larger amplitude of the fast ice movement at the latter site relative to the two, more eastward, beacons could be taken, in part, as evidence of a greater fractional thick ice content in the western portion of the formerly thin ice/open water area. Alternatively the noted differences could also reflect longitude-dependent variations in the strength of the regional landfast ice cover. Tests of these interpretations require additional annual GPS measurement programs utilizing presently available 5 decimal degree resolution positioning capabilities and the coordinated data taking essential for differential mode operations. Nevertheless, it can be concluded that present GPS capabilities are sufficient for detection and study of most relevant 1 m-2 m scale landfast ice movements without recourse to differential mode operations.

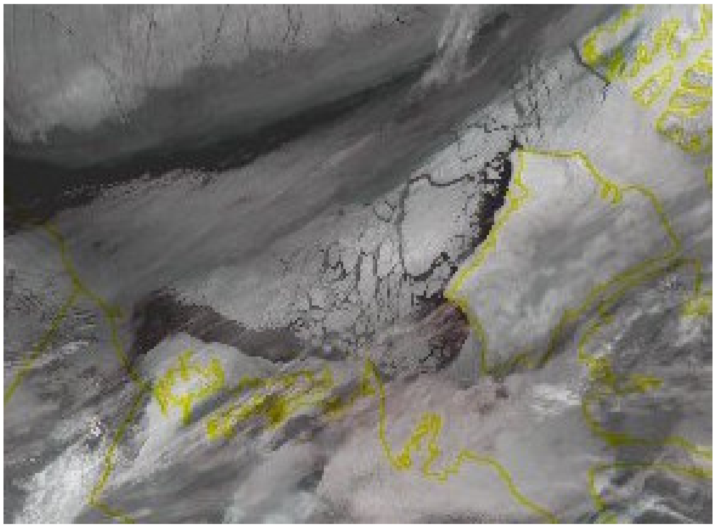


Figure 7. A NOAA AVHRR images of the study area (March 14, 2003)

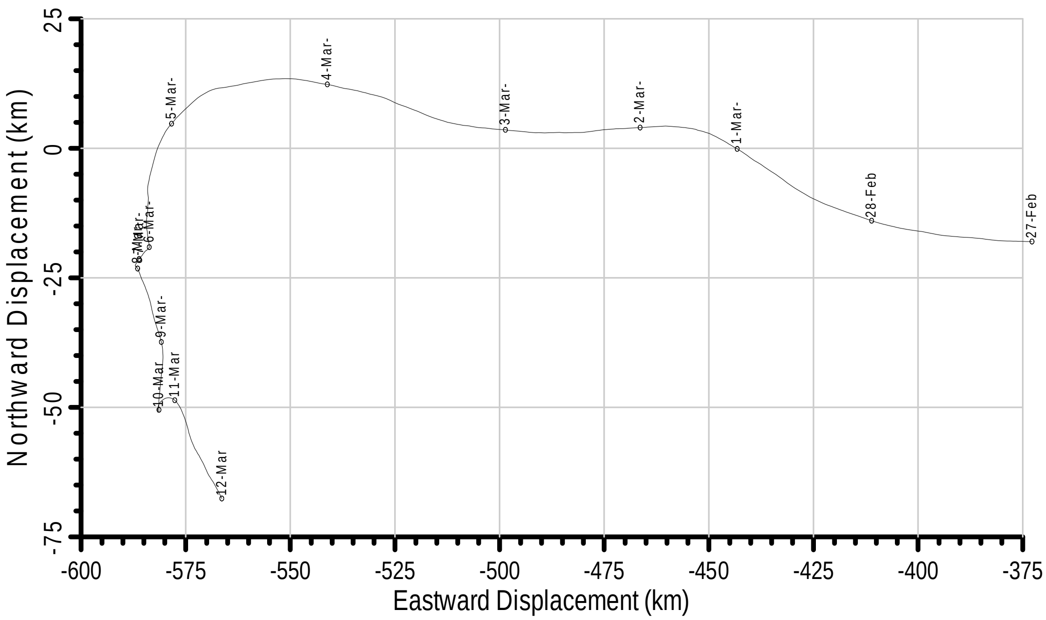


Figure 8. Cumulative northward and eastward displacements at the offshore site indicated in Figure 1 (Data and graphics provided by H. Melling.)

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Van der Baaren, A. and S.J. Prinsenberg, 2000. Satellite-tracked ice beacon tests for accuracy and positioning, 1997-1998. *Canadian Technical Report of Hydrography and Ocean Sciences*, # 209, 33p.