# Canadian Technical Report of Hydrography and Ocean Sciences 209

2000

# Satellite-tracked Ice Beacon Tests for Accuracy and Positioning,1997-1998

by

A. van der Baaren•

and

S. J. Prinsenberg

Ocean Sciences Division

Maritimes Region

Fisheries and Oceans Canada

Bedford Institute of Oceanography

P. O. Box 1006

Dartmouth, Nova Scotia

Canada, B2Y 4A2

• contractor, P. O. Box 1524, Wolfville, N. S., B0P1X0

Cat. No. FS 97-18/209E ISSN 0711-6764

Correct Citation for this publication:

van der Baaren, A. and S. J. Prinsenberg, 2000. Satellite-tracked Ice Beacon Tests for Accuracy and Positioning, 1997-1998. Can. Tech. Rep. Hydrogr. Ocean. Sci. 209: vii + 47 p.

# CONTENTS

# ABSTRACT

van der Baaren, A. and S. J. Prinsenberg. 2000. Satellite-tracked Ice Beacon Tests for Accuracy and Positioning, 1997-1998. Can. Tech. Rep. Hydrogr. Ocean. Sci. 209: vii + 47 p.

Stationary test results for absolute accuracy and relative positioning of satellite-tracked GPS location beacons are described for testing that took place in 1997 and 1998. It was found that reported beacon positions deviated from their mean, on average, by approximately 30-40 m and returned 90-100% of possible data. Relative positions were reported with mean RMS deviations from 6-30 m. Results show that there is a significant difference in reporting relative accuracy depending on whether or not two beacons obtained fixes from the same satellite constellations. RMS deviations improved two-fold if beacons obtained fixes from the same satellite constellations. Relative accuracy was also found to depend on the type of GPS unit available to the manufacturer.

# RÉSUMÉ

van der Baaren, A. and S. J. Prinsenberg. 2000. Satellite-tracked Ice Beacon Tests for Accuracy and Positioning, 1997-1998. Can. Tech. Rep. Hydrogr. Ocean. Sci. 209: vii + 47 p.

La présente décrit les résultats d’essais stationnaires tenus en 197 et 1998 et visant à mesurer l’exactitude absolue et le positionnement relatif de radiobalises de localisation par GPS. On a constaté que les positions indiquées par les balises variaient de leur moyenne d’environ 30 à 40 m et que ces dernières retransmettaient de 90 à 100 pour 100 des données possibles. Les positions relatives étaient indiquées avec des écarts moyens d’une valeur efficace de 6 à 30 mètres. Les résultats montrent qu’il existe une différence considérable entre l’indication de l’exactitude relative si deux balises ont obtenu ou non des points des mêmes constellations de satellites. Les écarts de la valeur efficace sont réduits du double lorsque les balises obtiennent des points des mêmes constallations de satelllites. On a aussi constaté que l’exactitude relative dépendait du type de dispositif GPS utilisé par le fabricant.

# LIST OF TABLES

# LIST OF FIGURES

# 1 INTRODUCTION

Mobile pack ice off Canada's east coast severely limits winter navigation in the region. Satellite imagery provides magnitudes and spatial extent of sea-ice concentration and movement. RADARSAT is able to estimate ice pressure and convergence/divergence with an accuracy of tens of metres (Peterson and Prinsenberg, 1993). Ice pressure specifically inhibits ship maneuverability. In addition, ice pressure greatly increases the risk of damage to offshore, man-made structures.

Satellite-tracked ice beacons equipped with Global Positioning System (GPS) receivers supplement satellite imagery data with a higher resolution data record of tracked sea ice movement. These GPS data serve a dual purpose. Not only can pack ice movement be frequently monitored in a relatively cost-effective manner, but the high position accuracy provided by the GPS means that, theoretically at least, the convergence/divergence of pack ice can be quantified to within metres. The quantification, in turn, can be related to stress found within the ice pack.

From 1995 to 1998, GPS beacons were deployed off the coast of Labrador and in the Gulf of St. Lawrence as part of the sea ice field program at the Bedford Institute of Oceanography. Before any field deployment of the GPS location beacons was performed, however, reliability of the instrument had to be assured. This was done by running stationary ground tests of position data accuracy, both of the absolute position of a single beacon and of the position of one beacon relative to another. Accuracy was determined through computations of standard error/RMS.

Results have been published from the accuracy tests performed in 1995 and 1996 on instruments built by Seimac, Ltd. of Dartmouth, Nova Scotia (Prinsenberg, et al., 1997; Prinsenberg, et al., 1998). The 1995 tests provided a benchmark in accuracy to which all other beacon tests were compared. The benchmark standards are:

1) To provide hourly data 93% of the time with an absolute positional accuracy of 37 m
2) To provide hourly data with a mean relative distance accuracy of 17 m and an 87% data return when using observed positions regardless of the satellite constellations used by the two beacons to determine their fixes
3) To provide hourly data with a mean relative distance accuracy of 1.7 m and a 55% data return when using positions observed only when the two beacons obtained fixes from the same satellite constellations.

In 1997, besides the Seimac instruments, GPS location beacons built by METOCEAN Data Systems, Ltd., of Dartmouth, Nova Scotia were tested.

This technical report will present details of the stationary tests performed in 1997 and 1998. Included in the document are descriptions of each manufacturer's beacons and the configuration of each test (Instrumentation and Data Collection). Statistics of absolute and relative accuracy are presented in the section entitled Data Processing and Summary.

Final conclusions about the success of the beacons in attaining the objectives of the tests, as set by the 1995 results, are given in the section entitled Summary of Results.

# 2 INSTRUMENTATION AND DATA COLLECTION

Each instrument is equipped with a GPS engine that uses satellite constellations to obtain position fixes. The way in which the GPS satellites are configured provides positioning in time and space from anywhere between 5 and 8 space vehicles (Dana, P. 1999). After initial magnetic activation (by removing a magnet located on the instrument casing) at the time of deployment, the beacon turns itself off and then powers-up near the top of every hour to obtain the positional fix from any GPS satellites it observes.

Although data are gathered once per hour, data messages are transmitted every 90 s. The instruments have the ability to retain 8 hours of data where 4 hours of data are transmitted in each of two alternating messages to passing satellites used by Service ARGOS. The 2 data messages are updated internally every time the beacon obtains new location fixes on the hour. The satellites gather transmissions from these beacons during their passes over deployment regions. A single satellite pass can result in several transmissions of the same recorded data. When the ice platform melts, data transmission stops so expendability of the instruments is configured into their cost. Since each brand of GPS beacon has its own unique features, details of each manufacturer’s beacon configuration follow this section.

Data transmissions include latitude, longitude, GPS time, GPS satellite constellation identification, and data quality filters. The Service ARGOS data which is downloaded contains, not only the GPS beacon data but also position information from the Service ARGOS satellites. The differences between the positioning from the GPS satellites and the ARGOS positions are frequency and accuracy. GPS positioning is more frequent and more accurate with less scatter.

## 2.1 SEIMAC GPS LOCATION BEACONS

Seimac, Ltd. provided two different GPS location beacons, a different one for each year 1997 (type I) and 1998 (type II). The difference in beacon configuration amounted to differences in electronic components used and differences in placement of internal components. In both years, though, the Seimac beacon components were contained in a sealed fiberglass shell and deployed with its bottom section in a shallow ice hole 12 cm across (Figure 1).

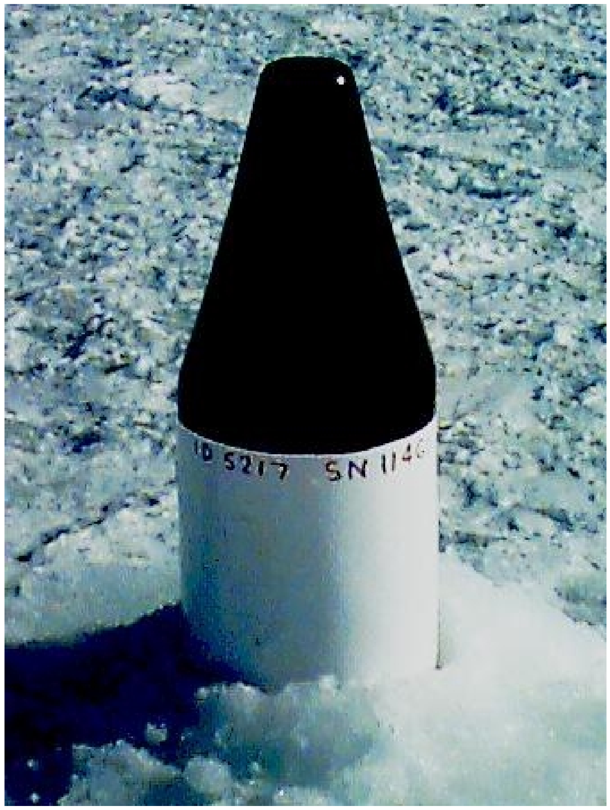


**Figure 1  Photo of 1997 Seimac GPS location beacon (type I).**

The top of the beacon was painted black so that it could absorb solar radiation and melt snow and ice build-up.  The unit was designed to sink when the ice platform melted.  The 1997 beacon weighed 65 lbs. and was 95 cm long and 10 cm in diameter at the bottom. The battery pack was in the bottom cylindrical section.  The battery pack could power the beacon for about 60 days at –35°C and 90 days at –20°C (Seimac, 1995).  The major electronic components were the Smart Cat© PTT (Platform Transmitter Terminal) and antenna, a GPS engine (Trimble CM2 OEM) and GPS antenna (Trimble FOG), battery pack and magnetic activation switch (Figure 2).

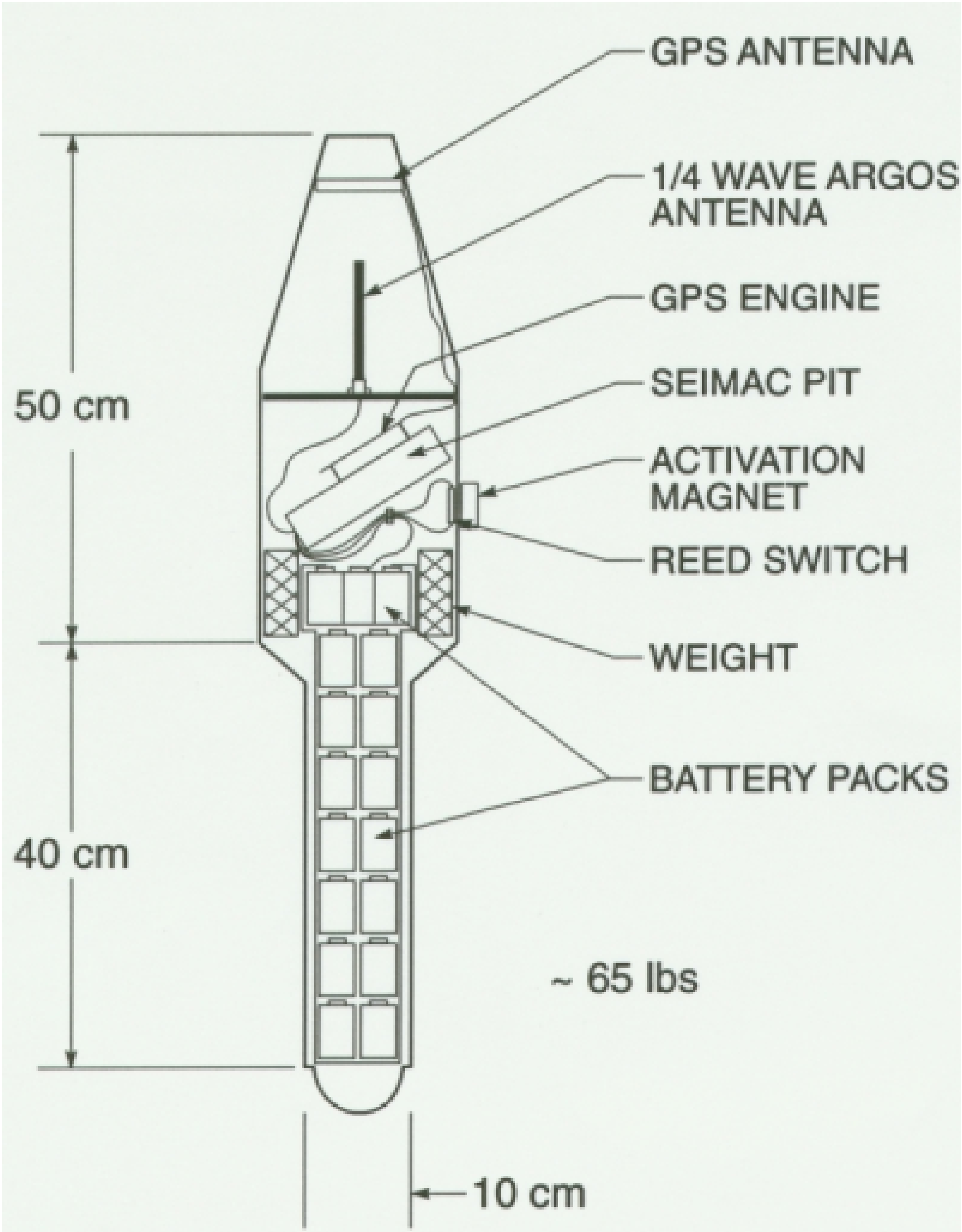


**Figure 2 Schematic diagram of 1997 Seimac (type I) GPS ice beacon (reproduced from Seimac, 1995).**

The unit which was tested in 1998 (type II) had the same basic electronic configuration except that the portion which showed above the snow was shortened since the electronics were now partially housed in the long cylindrical section. The GPS unit used in the 1998 Seimac units was the Trimble CM3 OEM (Seimac, 1998).

For both types of Seimac beacon the deployment and data transmission after deployment implemented the same procedures. At the time of deployment, once the beacon was turned on, the PTT sent a message every 90 s to the ARGOS satellite system. These first transmissions were monitored with a standard, handheld, ARGOS PTT test-set to assure proper functioning. Once the GPS obtained its first valid positional fixes, the PTT internal clock synchronized to the GPS real time. The system shut itself down to wait for the turn of the next hour.

After deployment, the GPS engine self-activated at 5 min before every hour to obtain new fixes. After powering-up, the GPS sent a navigational message every 5 s to the PTT. The last message before the hour was logged and a new message was calculated for transmission by the PTT. On the hour (within 5 s), the beacons logged their positions and the satellite constellations used to fix their positions. The 8 most recent positions were stored. The PTT internal clock was resynchronized after every hourly fix and a new ARGOS message was compiled and transmitted. Aside from the positional information the beacons were equipped to record and transmit the GPS hour of the most recently recorded position, ice temperature, battery voltage, and flags to show the amount of time and the number of satellites used to obtain a fix. The data are transmitted as two, 32 byte messages to Service ARGOS satellites except for the time the beacon is first deployed and activated. At this time only a single message is transmitted until a fifth positional fix is obtained.

## 2.2 METOCEAN GPS LOCATION BEACONS

METOCEAN Data Systems also provided 2 different types of beacons for 1997 (type I) and 1998 (type II). Both types of METOCEAN GPS beacons were designed to sit in an ice hole with 4 arms extending radially from the top of a cylindrical casing to buoy the platform on the ice floe (Figure 3). The GPS receiver was located at the top of a mast, which extended from the cylinder, and the battery pack was hidden in the cylindrical case which rested in the ice hole (Figures 4 and 5). In the 1997 design, the mast was expandable (Figure 4) but in the 1998 design the mast was not expandable (Figure 6). The 1998 design also featured an antenna ground-plane which stretched out from the transmitter assembly to focus the transmission upwards.

The transmitter used in the both types of beacons was a METOCEAN MAT 906 and the ice temperature sensor was a YSI 44032 (METOCEAN, 1997). Both 1997 and 1998 beacons used a Rockwell Jupiter GPS engine.


**Figure 3  Photo of 1997 METOCEAN GPS location beacon (type I).**

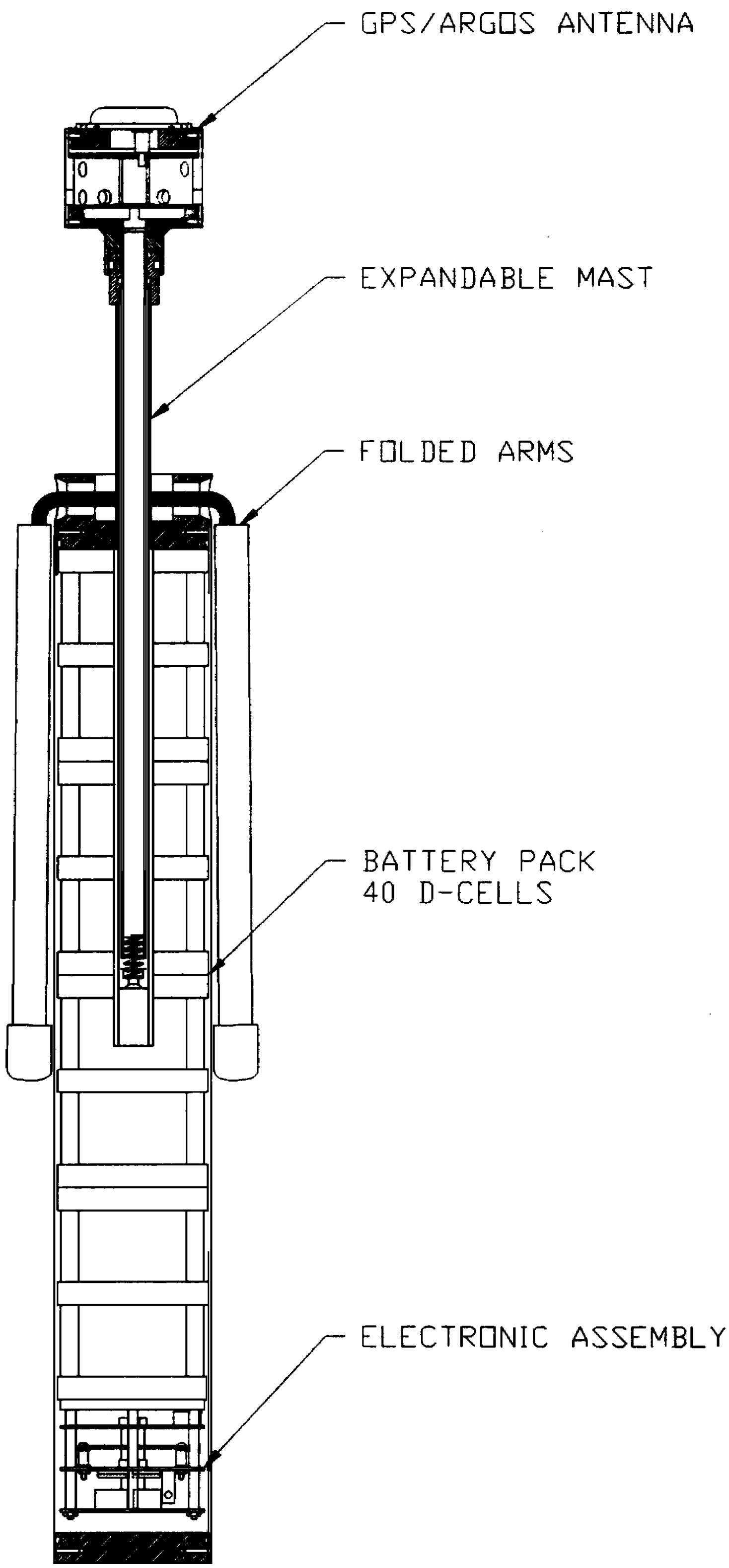


**Figure 4 Schematic diagram of 1997 METOCEAN, type I, location beacon (reproduced from METOCEAN, 1997).**

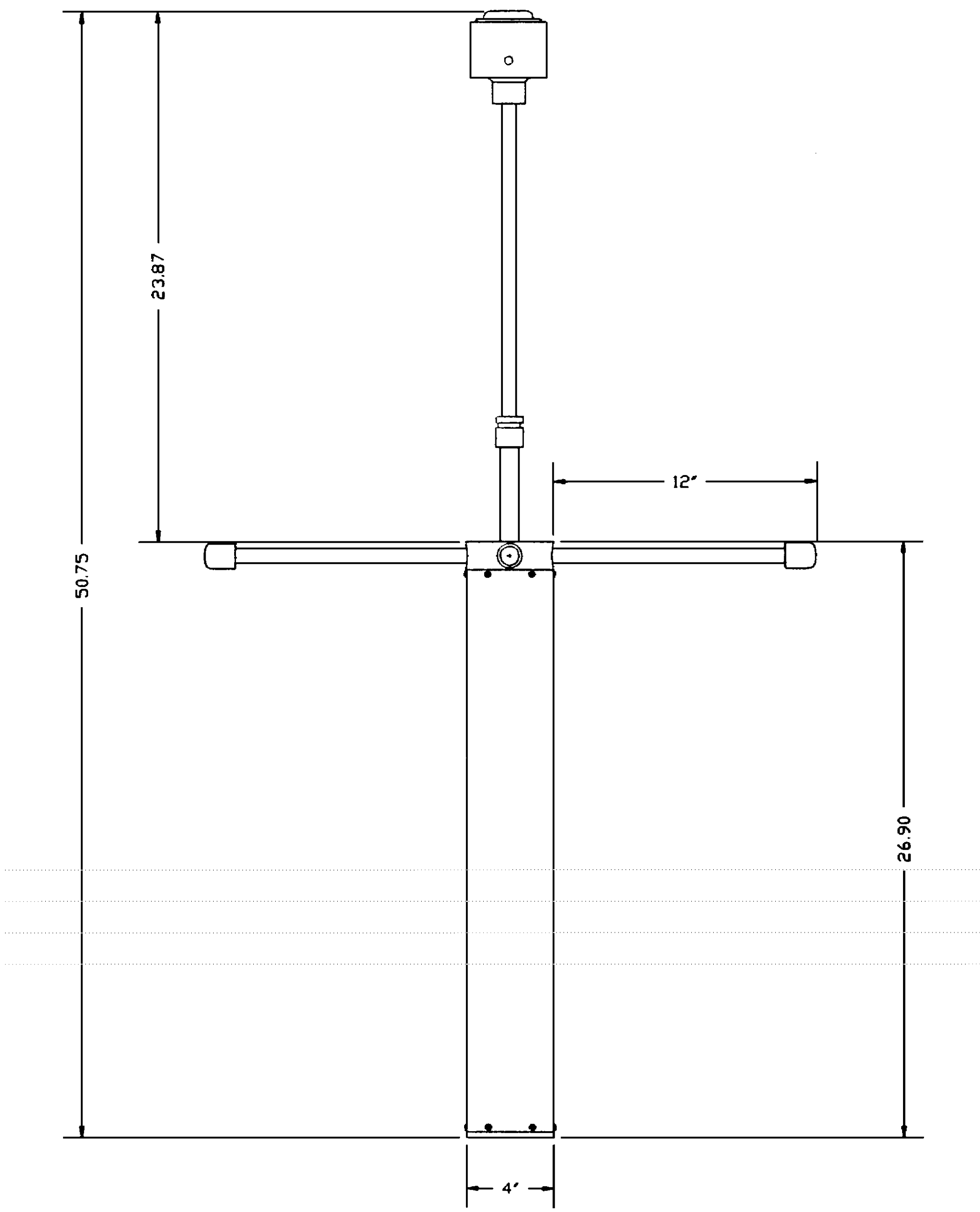


**Figure 5  Diagram of deployed 1997 METOCEAN, type I, GPS location beacon (reproduced from METOCEAN, 1997).**

Both types of METOCEAN beacons sampled positions once an hour such that they obtained their GPS fixes 10 s after the top of the hour (METOCEAN, 1998).  Updated positions were retained until the next fix was obtained an hour later.  The METOCEAN beacons transmitted latitudes, longitudes, GPS acquisition time, strength of the GPS signal, battery voltage, ice temperature, satellite constellation used to obtain the fixes, and data quality checks.  The quality checks were in the form of measures of the time it took to obtain a good fix and the measure of expected horizontal positional error.

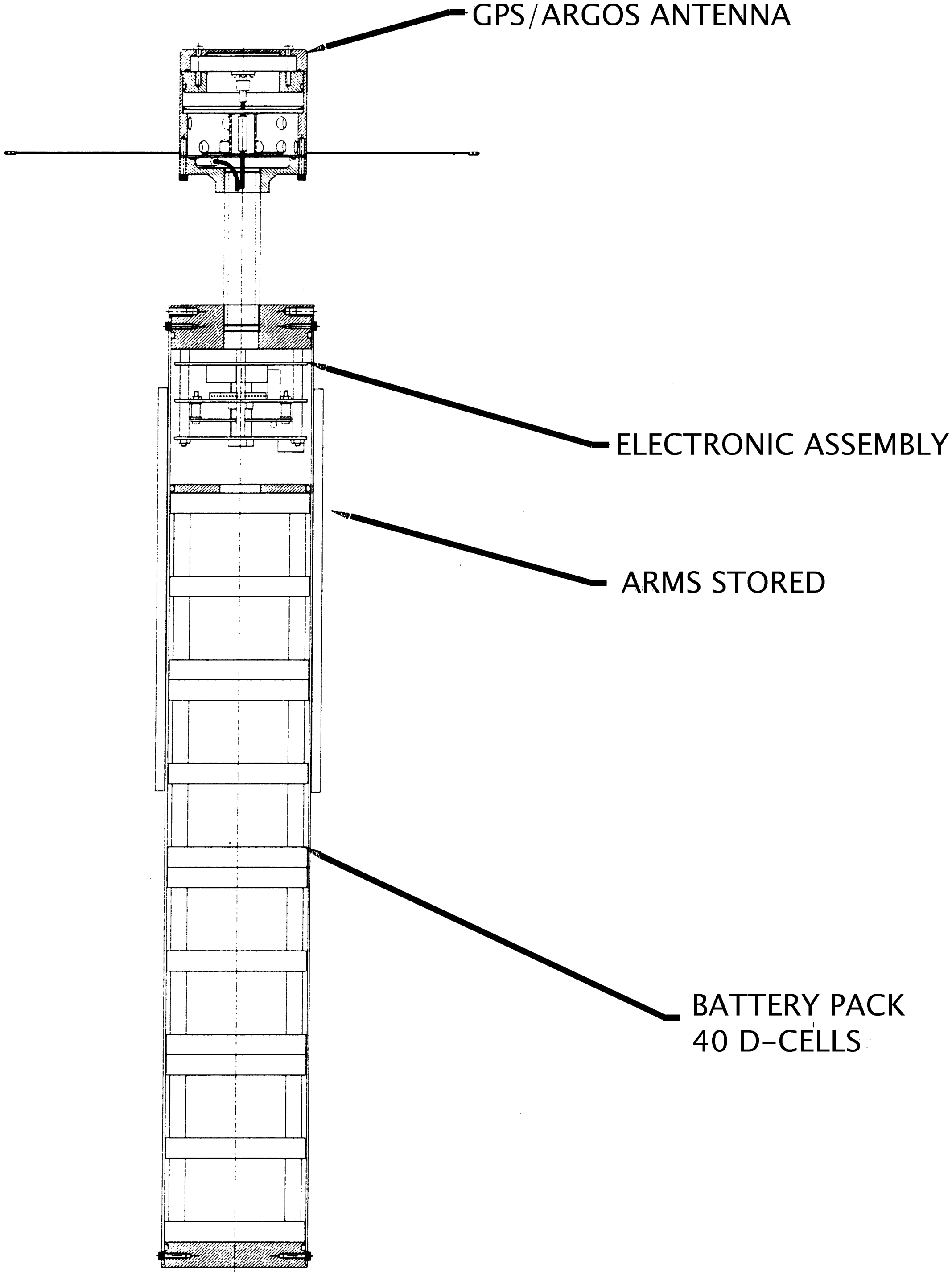


**Figure 6 Diagram of 1998 (type II) METOCEAN GPS location beacon with non-expandable mast.**

The 1998 version, type II, beacons also transmitted the calendar (Julian) day of when the positional fix was obtained. This datum was added in response to periodic errors which are discovered when constructing time series from beacon data.

## 2.3 TESTING ARRANGEMENT OF BEACONS

Stationary tests were conducted at the airport at CFB Shearwater, Nova Scotia (44.638 N, 63.515 W). Beacons were placed in a line, east to west, either 5 m or 10 m apart (Figure 6).

**Figure 7 1998 Seimac beacons (type II) are placed in line for stationary testing. The beacons were anchored in plastic buckets.**

Beacons were turned on from 2 to 4 days. Seimac beacons were tested separately from METOCEAN beacons although, at times, both brands of beacons were deployed simultaneously to take advantage of testing under similar meteorological conditions. Due to space limitations, no more than 10 beacons could be placed in line at a time.

**Figure 8  1998 METOCEAN beacons (type II) in line for stationary tests.  The beacons were anchored in plastic buckets.**

# 3  DATA PROCESSING AND SUMMARY

Test data were downloaded from Service ARGOS computer daily or every other day during the testing period.  These data were translated according to manufacturer's instructions and ordered into hourly time series.  Since ARGOS satellites received more than one transmission of similar recorded beacon messages during their regular passes, these messages were grouped according to the hour of positional recording and all messages for that hour would be summarized by computing the median value.  Therefore, the latitude and longitude in the time series for a specific hour is actually the median of all the latitudes–longitude pairs logged for that hour.  It should be noted that METOCEAN beacons required the use of $\pi$ to determine latitude and longitude values.  The precision used for $\pi$ was 9 decimal digits to assure precision of the translated positions.

The translation of the data included a check for data transmission errors.  The check was provided by checksums included in each transmitted message.  Each downloaded ARGOS message was translated into binary from its ASCII form and divided into bytes.  The sum of the bytes was compared to the transmitted checksum.  Unmatched checksums were tallied for all transmitted messages pertaining to a certain hour.  Medians were computed from all data transmitted for that hour if the percentage of unmatched checksums was less than 50%. Otherwise only the matched checksum data were used. If all checksums were not matched then all data were used so as not to lose possible data for that hour. It was found that unmatched checksums did not necessarily mean that data were unreliable.

Other built-in error checks, such as signal strength, were included in data messages but it was found that using these checks often eliminated perfectly good positions so counts were kept for these checks but no criteria were implemented for elimination of data using the counts.

The most notable data translation problem that arose was that of determining the proper time stamp to put on a transmitted data message. It was discovered that occasionally the GPS time that was reported to have been the hour of the most recent recorded position occurred *after* the ARGOS transmission took place. For example, the satellite pass may occur at 1400 on day 25 yet the reported GPS hour for the most recent fix is 2200 presumably for the same day. This is impossible. Due to the common occurrence of this error, it was requested that newer beacons be equipped with a Julian day stamp in their data message to record not only the hour at which the fix was made but also the day on which it was made. For the older beacons and for Seimac beacons, the occurrence of this error was flagged and if it occurred the day assigned to the recorded data was the previous day.

Data were plotted and edited for errors. Data errors were replaced with “missing value” flags. Descriptive statistics were computed for each record and then the distance between beacons was computed (relative distances). Descriptive statistics of these relative distances were computed.

Analysis of test data also included computing how many times a beacon recorded data within 200 m of its mean location. The mean location was the latitude and longitude of the test site. The ability of the beacon to determine its own location was defined as a test of absolute accuracy. Relative positioning accuracy was defined as the ability of a beacon to determine its position/distance relative to another beacon. Computation of individual beacon mean values excluded outliers, that is, points that were more than 0.015° from the mean latitude or longitude.

# 4 SUMMARY OF RESULTS

Results of all stationary tests are summarized in the 4 tables that follow. Each table lists the statistical analyses of available data.

## 4.1 ABSOLUTE ACCURACY

In the results for absolute accuracy, the first column gives the ratio of the number of beacons tested to the number of beacons that responded. The second column lists the total number of hours for the test.

"Direction" refers to the easterly and northerly distances as represented by latitudes and longitudes. Distance is the actual straight-line distance that the beacon is from its mean position. It is defined as $L = \sqrt{(x-\bar{x})^2 + (y-\bar{y})^2}$ where, $\bar{x}$ (63.515°W) is the mean longitude and $\bar{y}$ (44.638°N) is the mean latitude.

The RMS, σ, deviation is the standard deviation of the distance that each beacon's position deviated from its mean position (position of Shearwater = 44.638°N and 63.515°W). In effect:

$$\sigma = \sqrt{\frac{(x-\bar{x})^2}{n-1}}$$ where x = (position – position of Shearwater (or other test site).

The RMS deviations are described by their ranges and their means.

Data return is represented by the total number of data received relative to the total number of hours of the test.

### 4.1.1 1997 stationary tests

**Table 1 Table of results for absolute accuracy from 1997 stationary tests. All beacons are type I beacons.**

| | # beacons tested/# beacons responding | Total hours | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|---|---|
| | | | | Range | Mean | Range | Mean |
| **TEST 1 SEIM Type I** | 10/10 | 93 | East | 23-28 | **25.3** | 96-100 | **99.4** |
| | | | North | 39-44 | **39.9** | 96-100 | **99.4** |
| | | | Distance | 46-52 | **47.5** | 96-100 | **99.4** |
| drop a beacon | 9/10 | 93 | East | 23-27 | **25.1** | 96-100 | **99.4** |
| | | | North | 39-42 | **39.7** | 96-100 | **99.4** |
| | | | Distance | 56-49 | **47.0** | 96-100 | **99.4** |
| **TEST 2 METO Type I** | 14/14 | 72 | East | 31-48 | **38.6** | 89-100 | **97.6** |
| | | | North | 42-54 | **47.4** | 89-100 | **97.6** |
| | | | Distance | 55-68 | **61.4** | 89-100 | **97.6** |
| **TEST 3a SEIM Type I** | 4/4 | 71 | East | 24-25 | **24.7** | 97-100 | **99.3** |
| | | | North | 36-37 | **36.7** | 97-100 | **99.3** |
| | | | Distance | 44-45 | **44.2** | 97-100 | **99.3** |
| **TEST 3b METO Type I** | 4/4 | 72 | East | 34-35 | **34.1** | 99-100 | **99.5** |
| | | | North | 43-50 | **45.9** | 99-100 | **99.5** |
| | | | Distance | 55-61 | **57.2** | 99-100 | **99.5** |

In the first test, it was discovered that one Seimac beacon produced unusually inaccurate results. This can clearly be seen when comparing Figures 9 and 10. The scatter in Figure 9 for mean RMS is much greater when all the beacon analysis data are plotted due to one beacon's results only. When the data from this beacon were removed from the analysis, the range for the RMS narrowed (Figure 10) and the mean RMS decreased slightly. In the course of the entire 2 years of testing, several times data from faulty beacons were removed from analysis data sets.

### 4.1.2 1998 stationary tests

Note that some of the beacons tested in this year were manufactured in 1997 and care should be taken if comparing results between these beacons and those manufactured in 1998.

**Table 2 Table of results for absolute accuracy from 1998 stationary tests. Beacons are a mixture of type I and type II.**

| | # beacons tested/# beacons responding | Total hours | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|---|---|
| | | | | Range | Mean | Range | Mean |
| **TEST 1 METO Type II** | 10/10 | 93 | East | 18-19 | **18.6** | 81-90 | **86.3** |
| | | | North | 30-33 | **30.8** | 81-90 | **86.3** |
| | | | Distance | 35-37 | **37.0** | 81-90 | **86.3** |
| **TEST 2 METO Type II** | 10/10 | 66 | East | 21-22 | **21.4** | 95-100 | **98.5** |
| | | | North | 32-34 | **32.3** | 95-100 | **98.5** |
| | | | Distance | 38-40 | **38.8** | 95-100 | **98.5** |
| drop a beacon | 9/10 | 66 | East | 21-22 | **21.5** | 95-100 | **98.6** |
| | | | North | 32-34 | **32.3** | 95-100 | **98.6** |
| | | | Distance | 38-40 | **38.8** | 95-100 | **98.6** |
| **TEST 3[1] METO Type I** | 6/6 | 47 | East | 31-41 | **35.0** | 34-100 | **87.7** |
| | | | North | 42-84 | **53.3** | 34-100 | **87.7** |
| | | | Distance | 52-93 | **64.4** | 34-100 | **87.7** |
| **TEST 4 METO Type II** | 11/11 | 38 | East | 15-18 | **16.0** | 53-63 | **62.1** |
| | | | North | 23-25 | **24.2** | 53-63 | **62.1** |
| | | | Distance | 29-30 | **29.1** | 53-63 | **62.1** |
| drop a beacon | 10/11 | 38 | East | 15-16 | **15.8** | 63-63 | **63** |
| | | | North | 23-25 | **24.4** | 63-63 | **63** |
| | | | Distance | 29-30 | **29.1** | 63-63 | **63** |
| **TEST 5 SEIM Type II** | 10/10 | 45 | East | 24-33 | **27.2** | 98-100 | **99.8** |
| | | | North | 23-33 | **26.9** | 98-100 | **99.8** |
| | | | Distance | 34-44 | **38.3** | 98-100 | **99.8** |
| drop 2 beacons | 8/10 | 45 | East | 24-33 | **26.9** | 98-100 | **99.8** |
| | | | North | 23-33 | **27.1** | 98-100 | **99.8** |
| | | | Distance | 34-44 | **38.2** | 98-100 | **99.8** |
| **TEST 6a METO Type II** | 5/5 | 48 | East | 16-17 | **17.0** | 98-100 | **99.6** |
| | | | North | 22-23 | **22.5** | 98-100 | **99.6** |
| | | | Distance | 28-29 | **28.1** | 98-100 | **99.6** |
| **TEST 6b SEIM Type II** | 5/5 | 48 | East | 25-27 | **25.5** | 98-100 | **99.6** |
| | | | North | 23-28 | **25.4** | 98-100 | **99.6** |
| | | | Distance | 35-38 | **36.0** | 98-100 | **99.6** |
| **TEST 7a METO Type II** | 5/5 | 70 | East | 19-21 | **19.8** | 99-100 | **99.8** |
| | | | North | 26-32 | **27.4** | 99-100 | **99.8** |
| | | | Distance | 32-39 | **33.8** | 99-100 | **99.8** |
| **TEST 7b SEIM Type II** | 5/5 | 70 | East | 23-30 | **26.2** | 96-100 | **98.0** |
| | | | North | 29-38 | **31.9** | 96-100 | **98.0** |
| | | | Distance | 38-48 | **41.2** | 96-100 | **98.0** |

[1] These beacons were manufactured in 1997.

| | # beacons tested/# beacons responding | Total hours | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|---|---|
| | | | | Range | Mean | Range | Mean |
| **TEST 8[2] SEIM Type II** | 4/4 | 95 | East | 20-31 | **24.5** | 67-99 | **85.5** |
| | | | North | 28-38 | **33.1** | 67-99 | **85.5** |
| | | | Distance | 34-49 | **41.2** | 67-99 | **85.5** |
| **TEST 9[3] SEIM Type II** | 3/3 | 50 | East | 24-26 | **24.5** | 100-100 | **100.0** |
| | | | North | 24-28 | **26.3** | 100-100 | **100.0** |
| | | | Distance | 34-38 | **35.9** | 100-100 | **100.0** |
| **TEST 10[2] SEIM Type II** | 4/4 | 45 | East | 19-28 | **22.1** | 98-100 | **99.5** |
| | | | North | 26-34 | **29.6** | 98-100 | **99.5** |
| | | | Distance | 33-44 | **37.0** | 98-100 | **99.5** |
| **TEST 11[2] SEIM Type II** | 3/3 | 48 | East | 20-23 | **21.9** | 100-100 | **100.0** |
| | | | North | 31-35 | **32.3** | 100-100 | **100.0** |
| | | | Distance | 39-40 | **39.0** | 100-100 | **100.0** |

Little or no difference in absolute accuracy was attained in 1998 Tests 2 and 4 by dropping suspected faulty beacons's data from analyses. Nevertheless, the 1998 table for relative accuracy will show that there were indeed a faulty beacons in whose test data acted as outliers in analyses.

## 4.2 RELATIVE POSITIONING

The tables shown in this section present the statistical analyses for distances computed between pairs of beacons. Prinsenberg, et al. (1998) showed that there was a significant difference in data return and accuracy of computed distances depending on whether or not each beacon in a pair observed the same satellite constellations. This is why statistics are presented for times when the beacon pairs observed the same constellations and despite which constellations are observed.

"Direction" refers to the easterly and northerly distances the first beacon is from the second beacon as represented by latitudes and longitudes. Distance, in this table, is the actual straight-line distance that the beacons are from each other. It is defined as $L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ where $x_2 - x_1$, is the easterly distance (longitudinal distance) and $y_2 - y_1$ is the northerly distance (latitudinal distance).

[2] test site (mean position) = 44.684°N, 63.614°W
[3] test site (mean position) = 44.894°N, 63.705°W.

### 4.2.1 1997 stationary tests

**Table 3 Table of results for relative accuracy from 1997 stationary tests.**

| Using all constellations | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|
| | | Range | Mean | Range | Mean |
| **TEST 1 SEIM Type I** | East | 10-13 | **11.4** | 95-99 | **98.4** |
| | North | 12-19 | **13.9** | 95-99 | **98.4** |
| | Distance | 12-17 | **13.6** | 95-99 | **98.4** |
| drop a beacon | East | 10-12 | **11.4** | 96-99 | **98.6** |
| | North | 11-18 | **12.8** | 96-99 | **98.6** |
| | Distance | 11-16 | **12.7** | 96-99 | **98.6** |
| **TEST 2 METO Type I** | East | 39-48 | **42.2** | 87-97 | **95.0** |
| | North | 41-54 | **46.6** | 87-97 | **95.0** |
| | Distance | 38-49 | **41.8** | 87-97 | **95.0** |
| **TEST 3a SEIM Type I** | East | 8-10 | **8.4** | 98-99 | **98.5** |
| | North | 12-14 | **13.3** | 98-99 | **98.5** |
| | Distance | 11-12 | **11.6** | 98-99 | **98.5** |
| **TEST 3b METO Type I** | East | 31-38 | **34.4** | 98-99 | **98.5** |
| | North | 40-47 | **42.5** | 98-99 | **98.5** |
| | Distance | 37-40 | **39.0** | 98-99 | **98.5** |
| Using same constellations | **Direction** | **RMS deviations (m)** | | **Data return (%)** | |
| | | **Range** | **Mean** | **Range** | **Mean** |
| **TEST 1 SEIM Type I** | East | 2-6 | **2.5** | 77-82 | **79.8** |
| | North | 2-12 | **4.4** | 77-82 | **79.8** |
| | Distance | 1-10 | **3.4** | 77-82 | **79.8** |
| drop a beacon | East | 1-2 | **1.7** | 77-82 | **79.3** |
| | North | 2-3 | **2.6** | 77-82 | **79.3** |
| | Distance | 1-2 | **1.8** | 77-82 | **79.3** |
| **TEST 2 METO Type I** | East | 27-38 | **32.8** | 29-41 | **34.9** |
| | North | 32-45 | **37.9** | 29-41 | **34.9** |
| | Distance | 31-39 | **34.6** | 29-41 | **34.9** |
| **TEST 3a SEIM Type I** | East | 1-2 | **1.5** | 41-52 | **46.3** |
| | North | 3-4 | **3.3** | 41-52 | **46.3** |
| | Distance | 2-2 | **2.1** | 41-52 | **46.3** |
| **TEST 3b METO Type I** | East | 24-38 | **29.3** | 80-84 | **82.5** |
| | North | 26-36 | **31.3** | 80-84 | **82.5** |
| | Distance | 30-41 | **34.1** | 80-84 | **82.5** |

Once the faulty beacon was dropped in 1997 Test 1, the relative accuracy (using the same constellations) improved to within acceptable levels (less than 3 m for the mean RMS).

### 4.2.2 1998 stationary tests

**Table 4 Table of results for relative accuracy from 1998 stationary tests.**

In the table that follows, statistics are reported for analysis that was performed for all beacons that reported data. In subsequent analyses, when determining which beacons needed tweaking by the manufacturer, some beacons were not included in determination of relative positioning. Tests 5 to 11 are results for analyses of beacons that were sent back to the manufacturer to be tweaked and subsequently retested.

| Using all constellations | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|
| | | Range | Mean | Range | Mean |
| **TEST 1 METO Type II** | East | 3-5 | **4.1** | 81-86 | **84.8** |
| | North | 7-13 | **9.4** | 81-86 | **84.8** |
| | Distance | 4-7 | **5.9** | 81-86 | **84.8** |
| **TEST 2 METO Type II** | East | 6-26 | **8.0** | 95-98 | **97.1** |
| | North | 9-36 | **12.0** | 95-98 | **97.1** |
| | Distance | 6-27 | **8.6** | 95-98 | **97.1** |
| drop a beacon | East | 3-4 | **3.6** | 95-98 | **97.3** |
| | North | 5-7 | **6.1** | 95-98 | **97.3** |
| | Distance | 4-5 | **4.1** | 95-98 | **97.3** |
| **TEST 3 METO Type I** | East | 23-40 | **29.9** | 34-85 | **75.8** |
| | North | 31-72 | **41.9** | 34-85 | **75.8** |
| | Distance | 25-50 | **33.3** | 34-85 | **75.8** |
| **TEST 4 METO Type II** | East | 2-4 | **2.5** | 53-62 | **61.2** |
| | North | 3-5 | **3.8** | 53-62 | **61.2** |
| | Distance | 2-4 | **2.6** | 53-62 | **61.2** |
| drop a beacon | East | 2-3 | **2.2** | 63-63 | **63** |
| | North | 3-5 | **3.7** | 63-63 | **63** |
| | Distance | 2-3 | **2.2** | 63-63 | **63** |
| **TEST 5 SEIM Type II** | East | 18-29 | **21.8** | 98-100 | **99.8** |
| | North | 17-28 | **21.1** | 98-100 | **99.8** |
| | Distance | 16-25 | **19.4** | 98-100 | **99.8** |
| drop 2 beacons | East | 18-28 | **21.1** | 98-100 | **99.8** |
| | North | 17-28 | **20.3** | 98-100 | **99.8** |
| | Distance | 17-24 | **19.3** | 98-100 | **99.8** |
| **TEST 6a METO Type II** | East | 3-4 | **3.2** | 98-99 | **98.8** |
| | North | 5-9 | **6.2** | 98-99 | **98.8** |
| | Distance | 3-6 | **4.0** | 98-99 | **98.8** |
| **TEST 6b SEIM Type II** | East | 15-18 | **16.5** | 98-99 | **98.8** |
| | North | 14-18 | **16.7** | 98-99 | **98.8** |
| | Distance | 15-18 | **16.2** | 98-99 | **98.8** |
| **TEST 7a METO Type II** | East | 6-10 | **7.6** | 99-100 | **99.8** |
| | North | 7-15 | **9.1** | 99-100 | **99.8** |
| | Distance | 5-9 | **6.6** | 99-100 | **99.8** |
| **TEST 7b SEIM Type II** | East | 23-30 | **26.1** | 95-98 | **96.6** |
| | North | 23-37 | **28.0** | 95-98 | **96.6** |
| | Distance | 21-31 | **24.2** | 95-98 | **96.6** |
| **TEST 8 SEIM Type II** | East | 25-32 | **27.6** | 61-80 | **72.0** |
| | North | 28-31 | **29.7** | 61-80 | **72.0** |
| | Distance | 25-27 | **25.8** | 61-80 | **72.0** |
| **TEST 9 SEIM Type II** | East | 15-21 | **16.9** | 100-100 | **100.0** |
| | North | 16-18 | **17.2** | 100-100 | **100.0** |
| | Distance | 14-18 | **15.5** | 100-100 | **100.0** |

| Using all constellations | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|
| | | Range | Mean | Range | Mean |
| **TEST 10 SEIM Type II** | East | 19-26 | **21.7** | 98-99 | **98.8** |
| | North | 17-21 | **18.9** | 98-99 | **98.8** |
| | Distance | 19-25 | **20.6** | 98-99 | **98.8** |
| **TEST 11 SEIM Type II** | East | 16-19 | **16.7** | 100-100 | **100.0** |
| | North | 16-23 | **18.2** | 100-100 | **100.0** |
| | Distance | 15-20 | **17.0** | 100-100 | **100.0** |

| Using same constellations | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|
| | | Range | Mean | Range | Mean |
| **TEST 1 METO Type II** | East | 2-5 | **3.2** | 75-81 | **78.7** |
| | North | 4-8 | **5.7** | 75-81 | **78.7** |
| | Distance | 3-6 | **3.8** | 75-81 | **78.7** |
| **TEST 2 METO Type II** | East | 5-23 | **6.8** | 27-88 | **80.3** |
| | North | 7-33 | **10.1** | 27-88 | **80.3** |
| | Distance | 5-22 | **6.9** | 27-88 | **80.3** |
| drop a beacon | East | 2-4 | **3.0** | 91-95 | **93.7** |
| | North | 3-5 | **4.2** | 91-95 | **93.7** |
| | Distance | 3-4 | **3.2** | 91-95 | **93.7** |
| **TEST 3 METO Type I** | East | 7-15 | **12.5** | 6-63 | **46.5** |
| | North | 22-35 | **26.9** | 6-63 | **46.5** |
| | Distance | 16-22 | **18.9** | 6-63 | **46.5** |
| **TEST 4 METO Type II** | East | 2-4 | **2.5** | 52-62 | **60.8** |
| | North | 3-5 | **3.8** | 52-62 | **60.8** |
| | Distance | 2-4 | **2.6** | 52-62 | **60.8** |
| drop a beacon | East | 2-3 | **2.2** | 63-63 | **63** |
| | North | 3-5 | **3.7** | 63-63 | **63** |
| | Distance | 2-3 | **2.2** | 63-63 | **63** |
| **TEST 5 SEIM Type II** | East | 6-17 | **10.1** | 39-65 | **54.6** |
| | North | 5-14 | **9.6** | 39-65 | **54.6** |
| | Distance | 5-13 | **8.8** | 39-65 | **54.6** |
| drop 2 beacons | East | 6-9 | **7.2** | 42-66 | **57.4** |
| | North | 5-8 | **7.4** | 42-66 | **57.4** |
| | Distance | 5-8 | **6.8** | 42-66 | **57.4** |
| **TEST 6a METO Type II** | East | 3-4 | **3.2** | 98-99 | **98.8** |
| | North | 5-9 | **6.2** | 98-99 | **98.8** |
| | Distance | 3-6 | **4.0** | 98-99 | **98.8** |
| **TEST 6b SEIM Type II** | East | 9-12 | **9.8** | 67-74 | **70.6** |
| | North | 6-13 | **9.5** | 67-74 | **70.6** |
| | Distance | 7-13 | **9.9** | 67-74 | **70.6** |
| **TEST 7a METO Type II** | East | 3-4 | **3.2** | 78-91 | **86.6** |
| | North | 4-5 | **4.2** | 78-91 | **86.6** |
| | Distance | 3-4 | **3.1** | 78-91 | **86.6** |
| **TEST 7b SEIM Type II** | East | 7-11 | **8.5** | 32-52 | **41.8** |
| | North | 8-12 | **10.1** | 32-52 | **41.8** |
| | Distance | 7-11 | **9.6** | 32-52 | **41.8** |

| Using same constellations | Direction | RMS deviations (m) | | Data return (%) | |
|---|---|---|---|---|---|
| | | Range | Mean | Range | Mean |
| **TEST 8** | East | 4-12 | **8.9** | 7-20 | **13.8** |
| **SEIM** | North | 6-11 | **7.3** | 7-20 | **13.8** |
| **Type II** | Distance | 4-12 | **7.8** | 7-20 | **13.8** |
| **TEST 9** | East | 4-5 | **4.6** | 45-55 | **50.7** |
| **SEIM** | North | 6-9 | **7.8** | 45-55 | **50.7** |
| **Type II** | Distance | 5-7 | **5.6** | 45-55 | **50.7** |
| **TEST 10** | East | 6-8 | **7.2** | 53-66 | **60.8** |
| **SEIM** | North | 6-10 | **7.7** | 53-66 | **60.8** |
| **Type II** | Distance | 5-7 | **5.9** | 53-66 | **60.8** |
| **TEST 11** | East | 6-9 | **7.7** | 53-60 | **55.8** |
| **SEIM** | North | 6-9 | **7.8** | 53-60 | **55.8** |
| **Type II** | Distance | 6-8 | **6.7** | 53-60 | **55.8** |

The table of relative accuracy for 1998 and the scatter plot of observed mean relative distances for 1998 Test 2 beacons (Figure 15) and Test 4 beacons (Figure 18) showed a wider than normal range of mean RMS. When suspected faulty beacons's data were removed from analyses the relative accuracy results in Table 4 improved remarkably. The scatter plots in the next section for 1998 Test 2 (Figures 16 and 17) and for 1998 Test 4 (Figures 18 and 19) verify the improvement.

Table 4 1998 Test 5 results show that removal of data gathered from faulty beacons improves analysis results for the Seimac type II beacons although the range in RMS deviations is still much greater than that of the type II METOCEAN beacons.

### 4.2.3 Scatter plots of observed mean relative distances

A record was kept of each beacon's deployment distance from east to west during some of the tests. Using these records Figures 9 to 17 show scatterplots of the relative accuracy means for measured distance and mean RMS of the measured distance both of which were plotted against the actual distance between pairs of beacons. In a perfect world, the measured distances should match the actual distances, but it can be seen that when all observed means are plotted, despite the constellations used by the beacons to obtain their GPS fixes, there is a large discrepancy between measured and true. However if the observations where the pair of beacons did not obtain fixes from the same satellite constellations are eliminated, the match between measured and true distance is extremely close. The range of the mean RMS of the distance between pairs of beacons also decreases when only observations obtained from the same constellations are used.

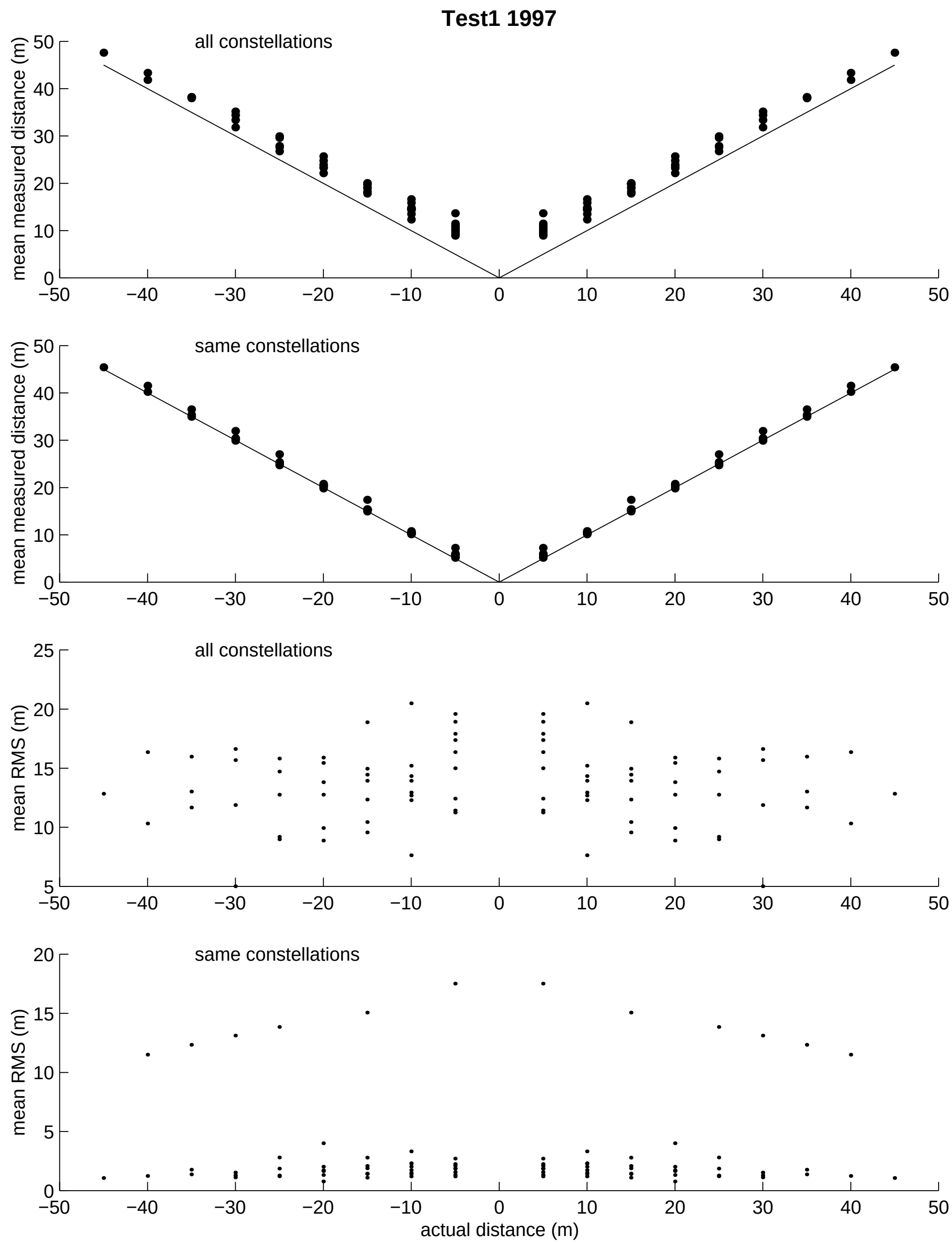


**Figure 9 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 1 in 1997 of type I Seimac beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

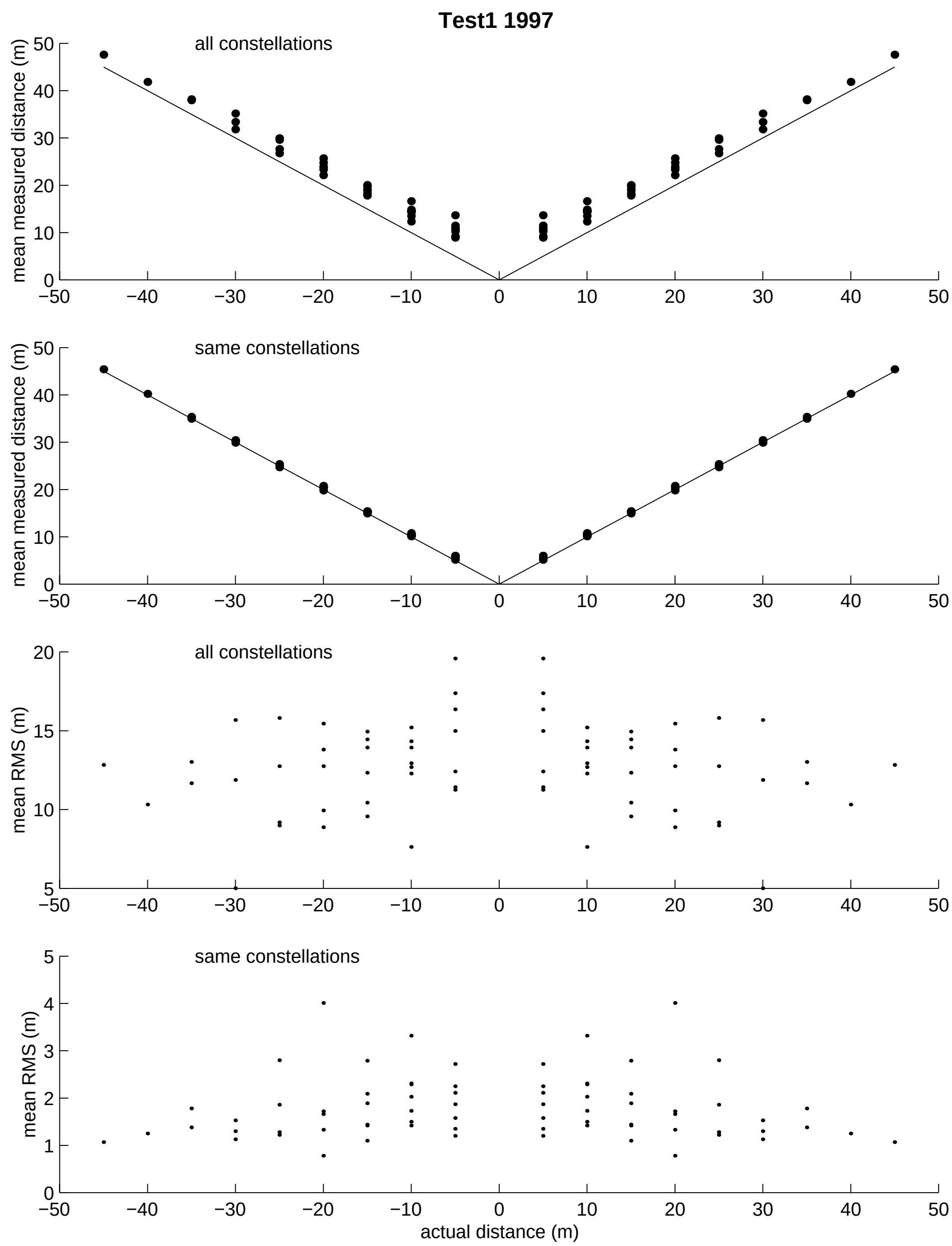


**Figure 10 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for 9 type I Seimac beacons in Test 1 in 1997 for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations. The outliers evident in Figure 9 no longer exist.**

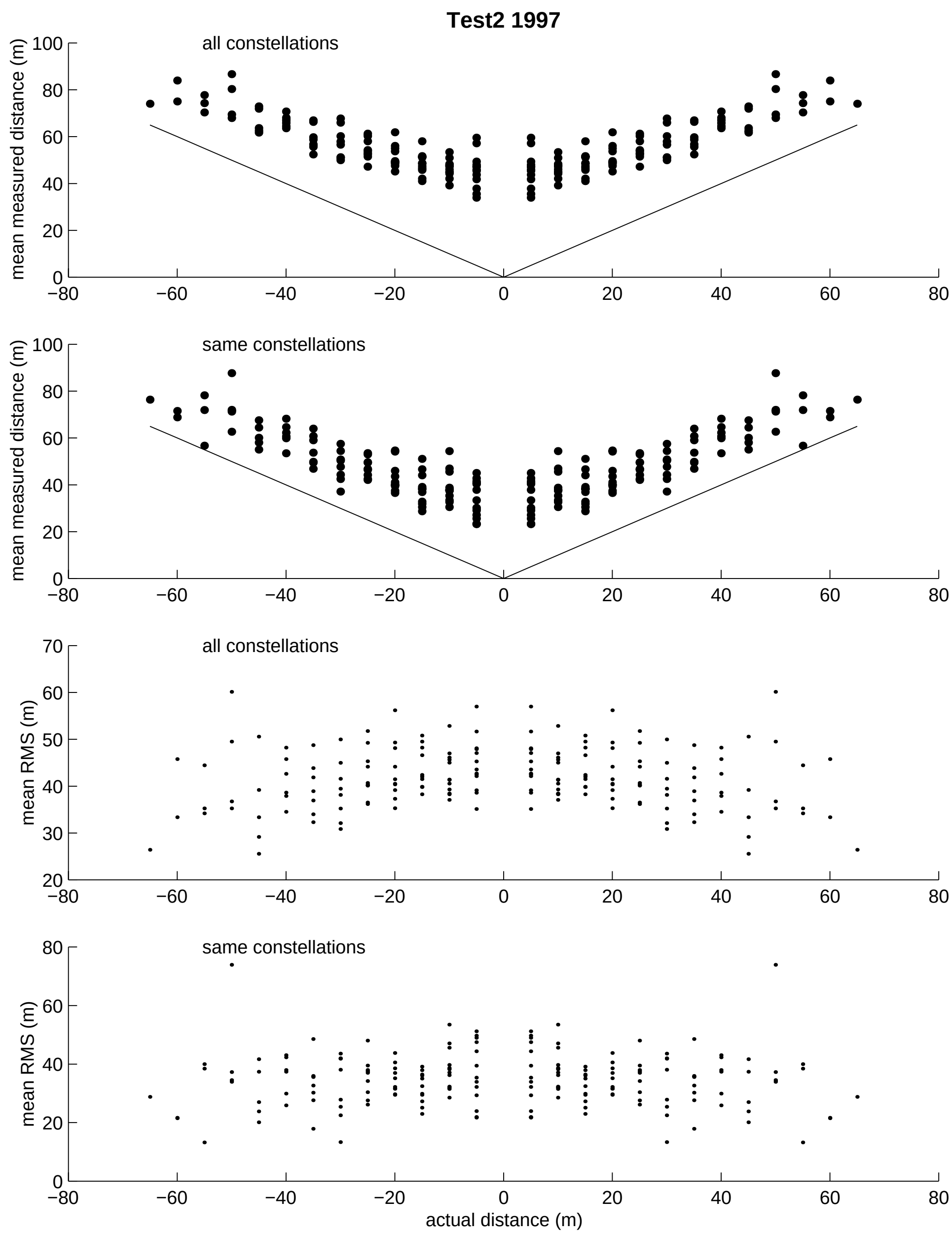


**Figure 11 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 2 in 1997 of type I METOCEAN beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

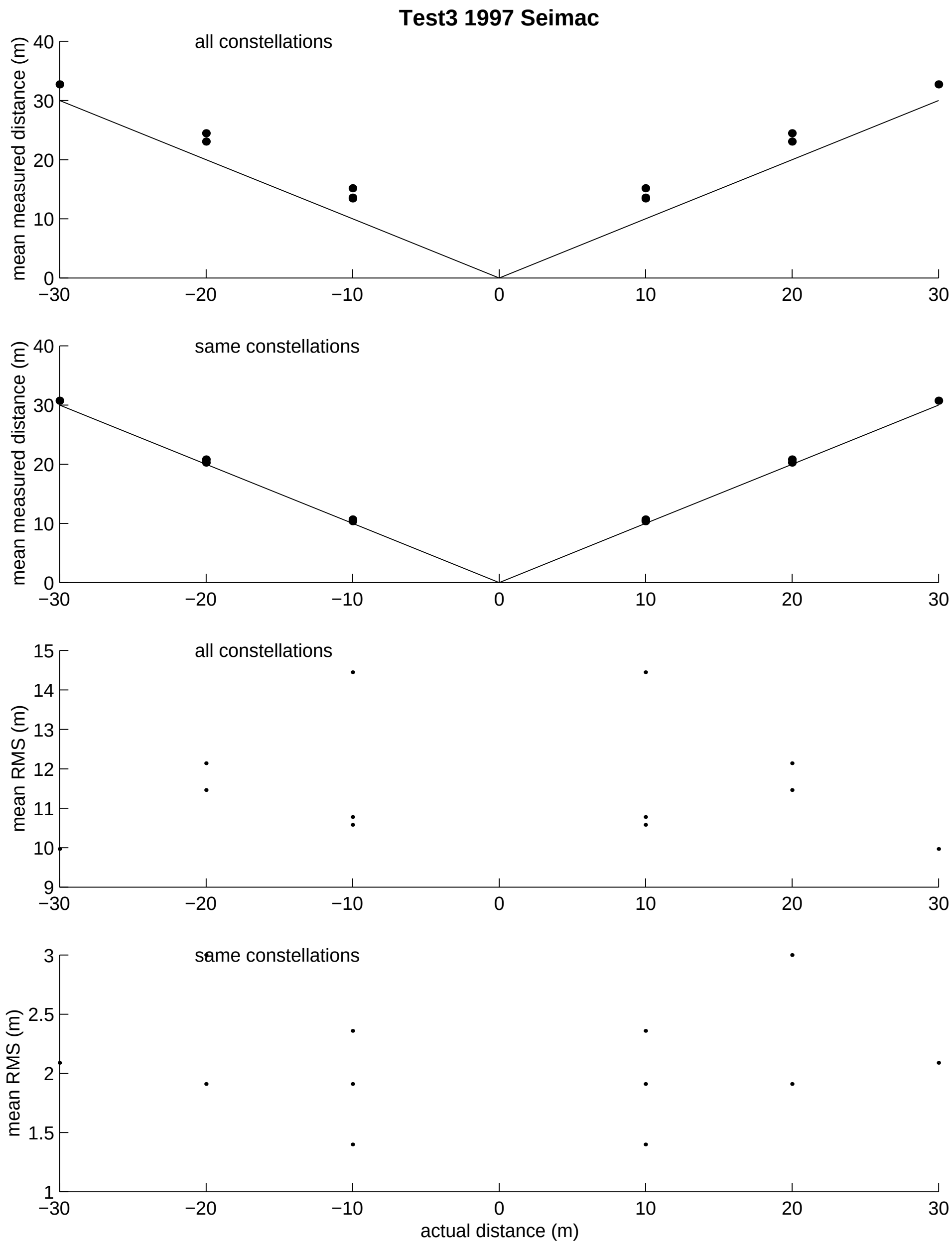


**Figure 12 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 3 in 1997 of type I Seimac beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

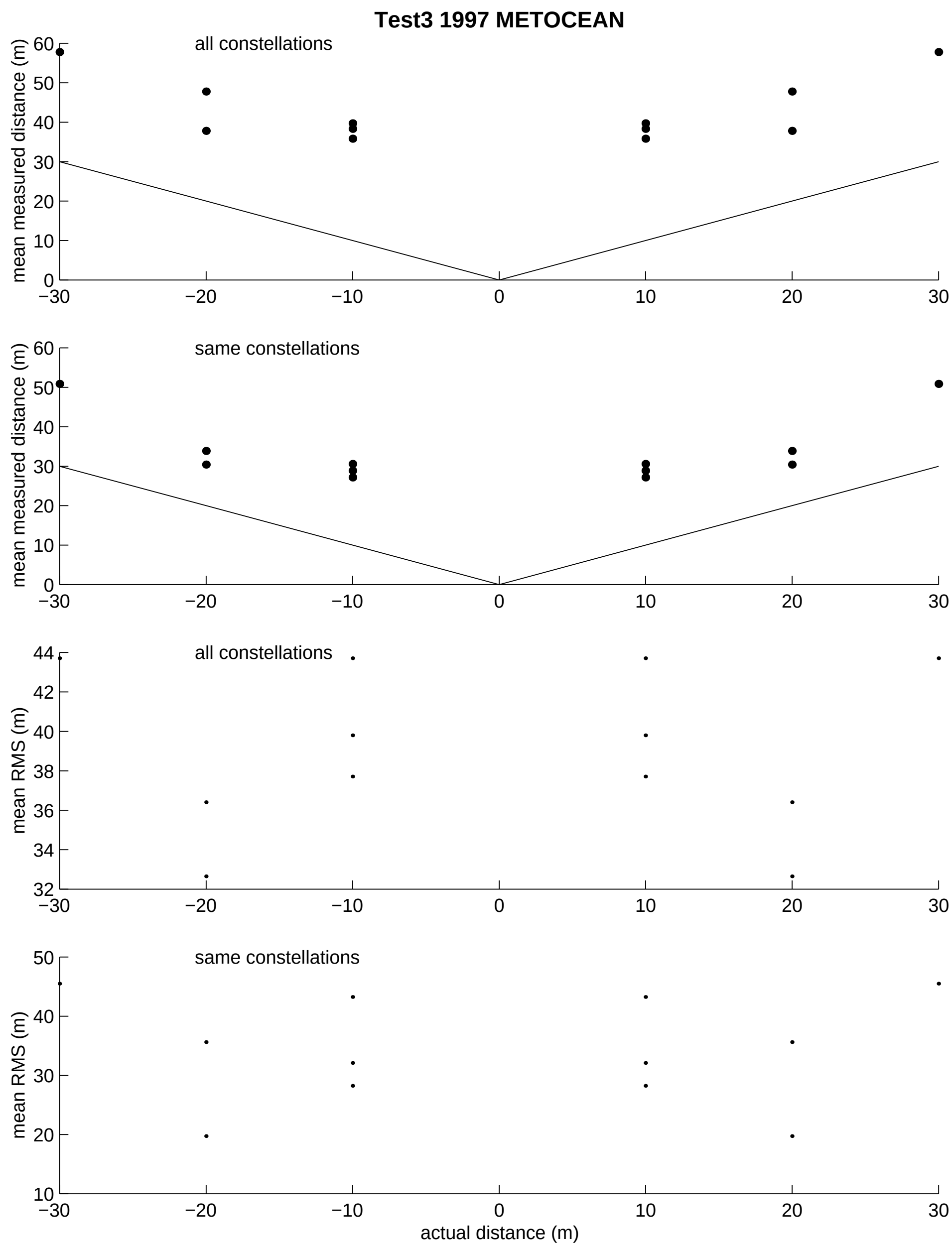


**Figure 13 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 3 in 1997 of type I METOCEAN beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

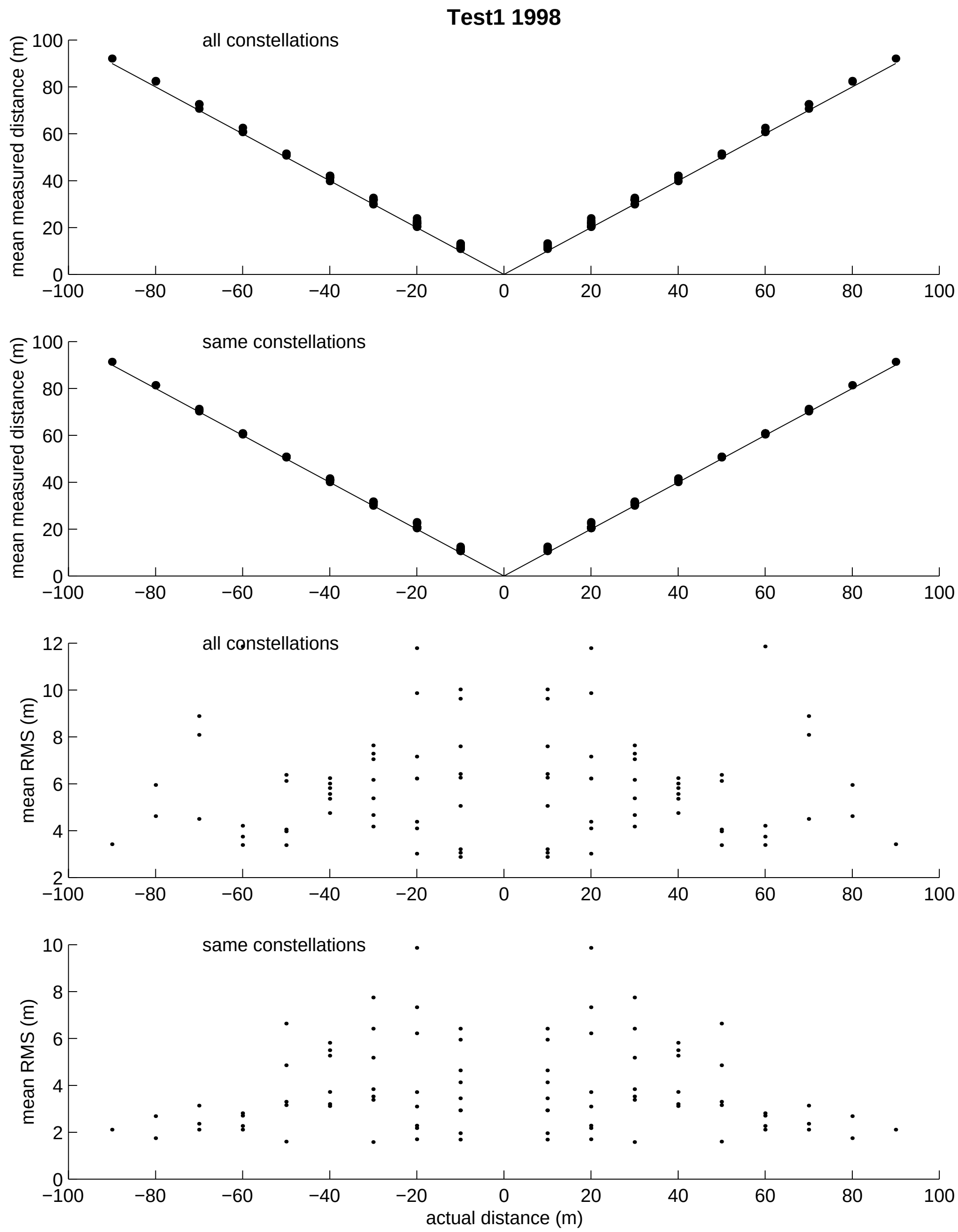


**Figure 14 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 1 in 1998 of type II METOCEAN beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

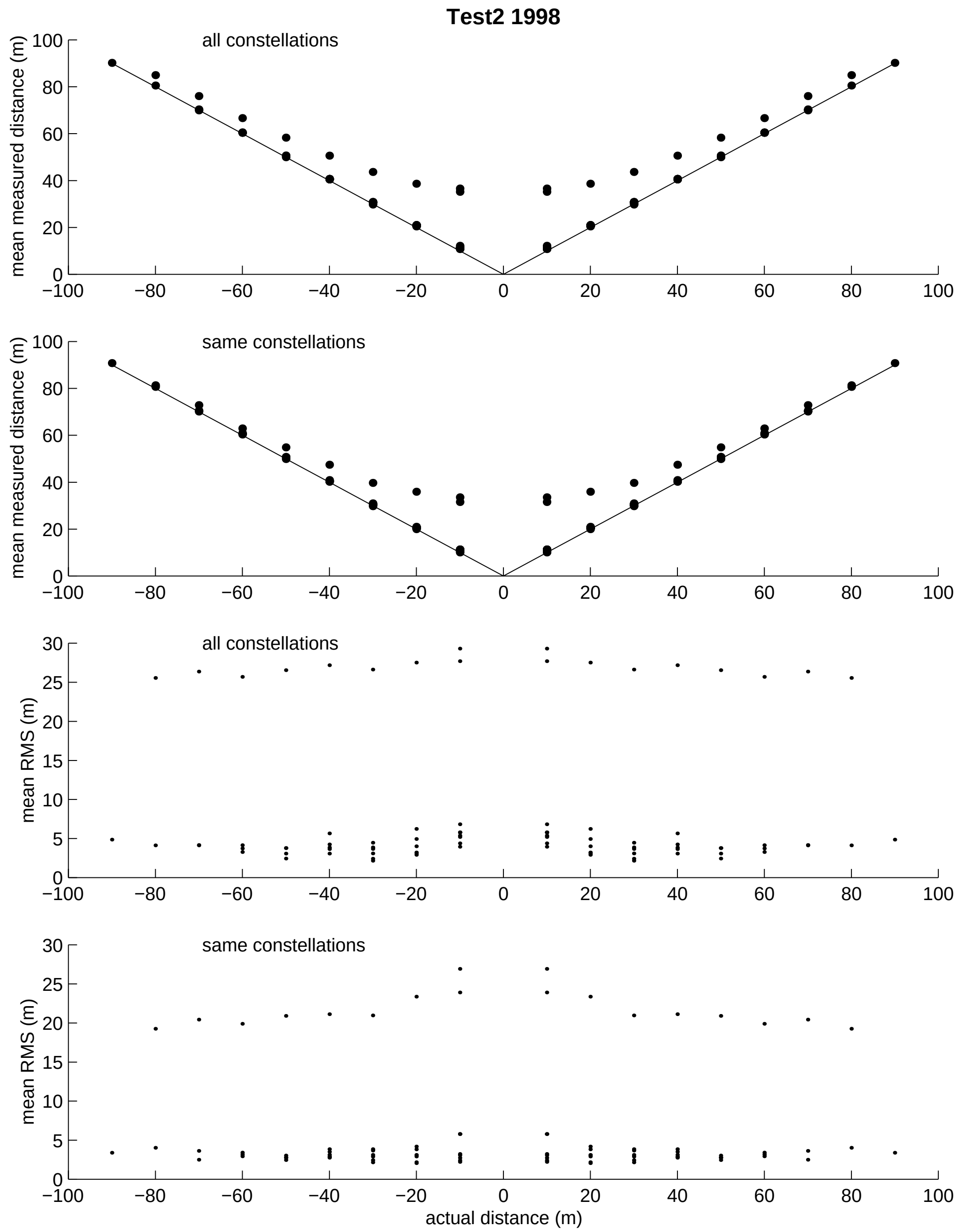


**Figure 15  Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance.  Plots are shown for Test 2 in 1998 of type II METOCEAN beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

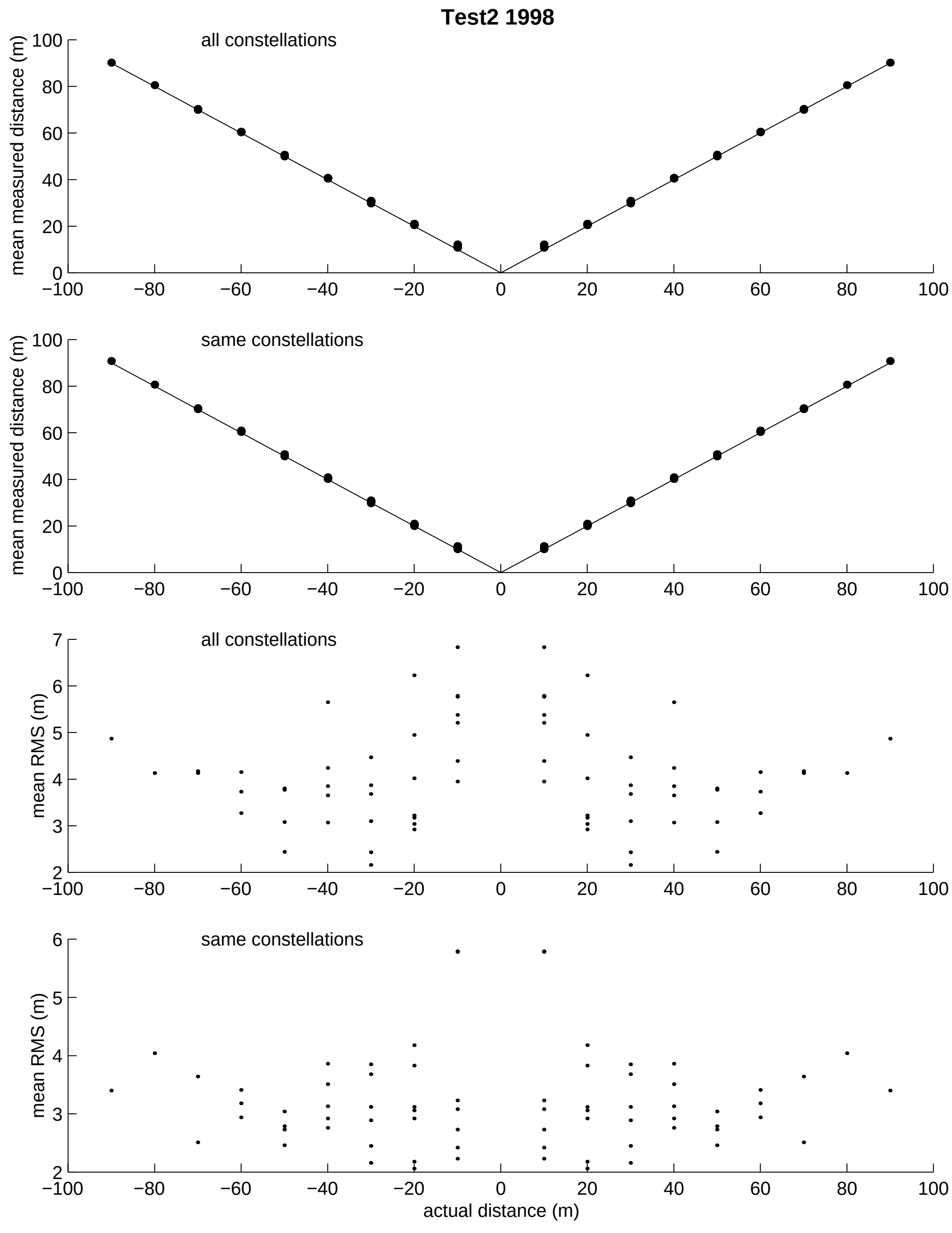


**Figure 16 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 2 in 1998 of type II METOCEAN beacons for when one beacon was dropped from data analysis.**

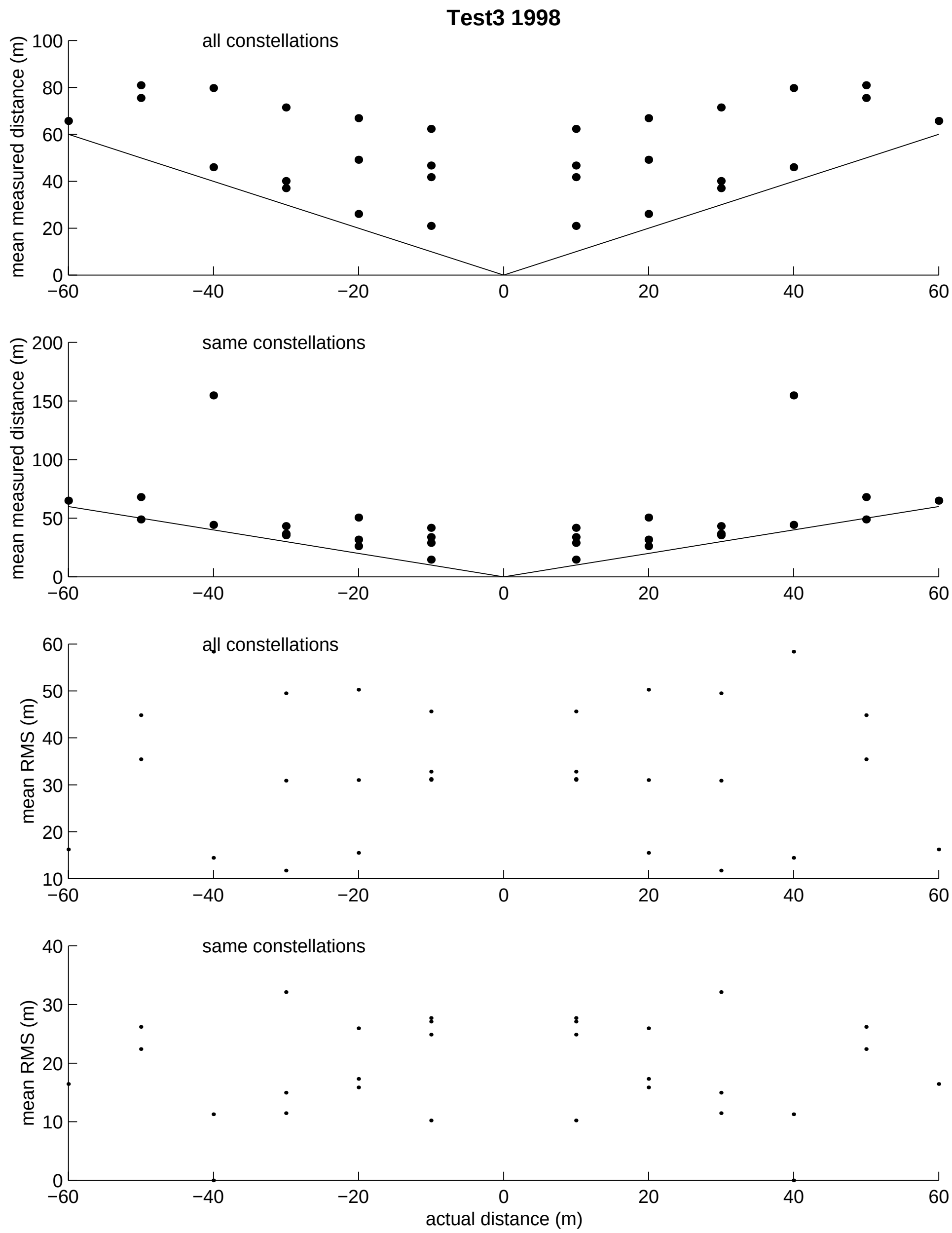


**Figure 17  Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance.  Plots are shown for Test 3 in 1998 of type I METOCEAN beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

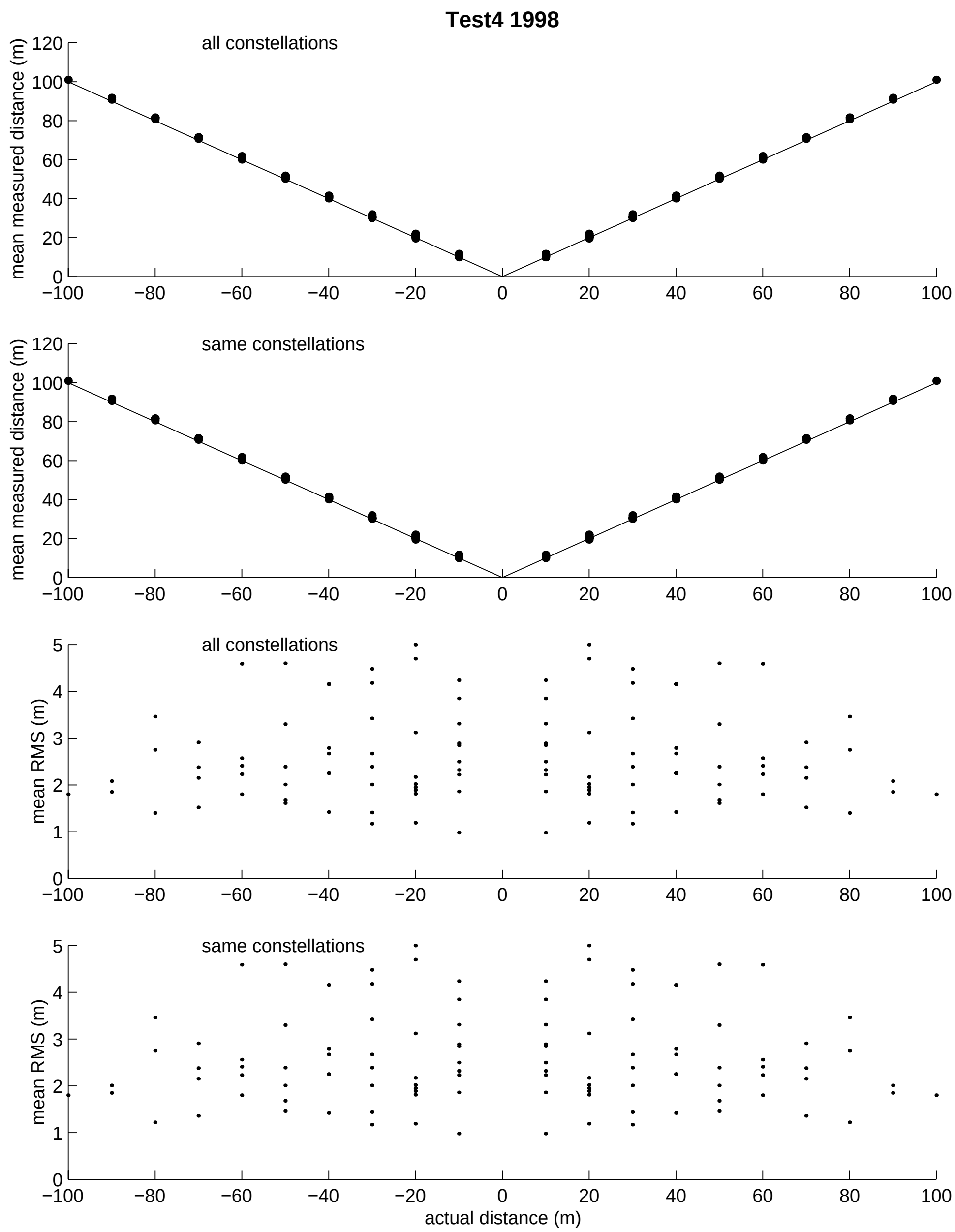


**Figure 18 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 4 in 1998 of type II beacons for when all observed satellites were used to obtain fixes and for when the two beacons observed the same satellite constellations.**

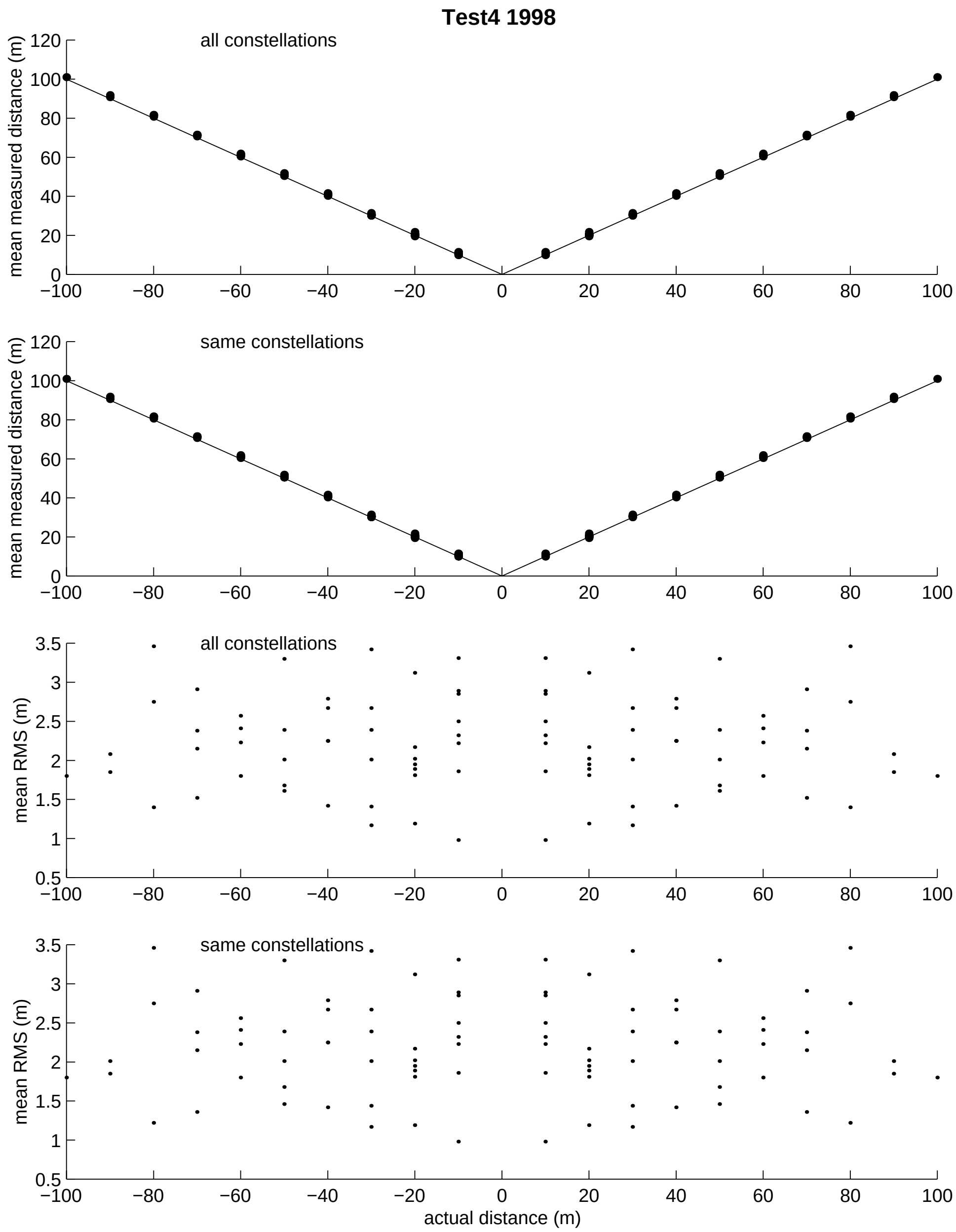


**Figure 19 Scatterplots of mean measured distance between beacons vs. actual distance between beacons and of mean RMS of measured distance between beacons vs. actual distance. Plots are shown for Test 2 in 1998 of type II beacons for when one beacon was dropped from data analysis.**

### 4.2.4 In summary

The shaded values in Tables 1-4 were averaged according to type of corresponding beacon. The means of the distance values are given below in Tables 5 and 6.

**Table 5 Summary table of mean results in absolute accuracy for distance measurements.**

| Absolute accuracy | mean | |
|---|---|---|
| | RMS deviations (m) | Data return (%) |
| **1997 type I Seimac** | 45.6 | 99.4 |
| **1998 type II Seimac** | 38.4 | 97.5 |
| **1997 type I MetOcean** | 61.0 | 94.9 |
| **1998 type II MetOcean** | 33.4 | 89.5 |

It is suspected that different GPS units installed in newer beacons resulted in the improvement of 1998 METOCEAN beacon results over the 1997 METOCEAN models.

**Table 6 Summary table of mean results in relative accuracy for distance measurements between pairs of beacons.**

| | mean | |
|---|---|---|
| **all constellations** | RMS deviations (m) | Data return (%) |
| **1997 type I Seimac** | 12.15 | 98.5 |
| **1998 type II Seimac** | 19.8 | 95.1 |
| **1997 type I MetOcean** | 38.0 | 89.8 |
| **1998 type II MetOcean** | 4.6 | 88.7 |
| **same constellations** | | |
| **1997 type I Seimac** | 2.0 | 62.8 |
| **1998 type II Seimac** | 7.5 | 50.1 |
| **1997 type I MetOcean** | 29.2 | 54.6 |
| **1998 type II MetOcean** | 3.3 | 84.2 |

Overall relative positions were reported with mean RMS deviations from 3-39 m. with the METOCEAN beacons showing the greatest improvement from year to year. The Seimac beacons had reduced relative accuracy due to the different GPS engines used from year to year. The GPS hardware difference was outside the control of the beacon manufacturer.

There is a significant difference in reporting relative accuracy depending on which satellite constellations the beacons used to obtain fixes. RMS deviations improved significantly if a pair of beacons obtained fixes from the same satellite constellations.

Compared with the benchmark set by the 1995 stationary tests, all types of beacons, except for the Type I MetOcean beacons, reported good data return of at least 95% with absolute accuracy better or near 37 m. Data return of at least 87% for relative accuracy of at least 17 m when all observed constellations were used for positional fixes was achieved by the Type I Seimac and Type II MetOcean beacons. When only positions obtained from the same satellite constellations were compared, only Type I Seimac and Type II MetOcean beacons achieved close to 1.7 m accuracy with a data return of at least 55%.

# 5 ACKNOWLEDGMENT

The researchers involved in this project gratefully acknowledge the financial support from the Panel of Energy Research and Development and logistical support from the Department of National Defence for the use of the CFB Shearwater testing ground. Ingrid Peterson and George Fowler gave invaluable assistance in the development and analysis of GPS beacons and data. They are duly thanked. I. Peterson is also thanked for proofreading this document. MetOcean Data Systems kindly provided ARGOS data for 1998 Tests 1, 2, and 4 for which we are grateful.

# 6 REFERENCES

METOCEAN Data Systems Ltd., 1998. Buoy-Specific Configuration for GPS Ice Beacons, METOCEAN No: 0602A000. METOCEAN Data Systems Ltd., Dartmouth, Nova Scotia, Canada, ii+12+app.

Dana, P. H. 1999. http://www.utexas.edu/depts/grg/gcraft/notes/gps/gps.html

----------, 1997. Buoy-Specific Configuration for GPS Ice Beacons, METOCEAN No: 0536A000. METOCEAN Data Systems Ltd., Dartmouth, Nova Scotia, Canada, ii+15+app.

Peterson, I. K., and S. J. Prinsenberg, 1993. Ice Drift off Newfoundland Derived from AVHRR Imagery and Ice Beacons. 16th Canadian Symposium on Remote Sensing, Sherbrooke, Quebec, Canada, pp. 227-232.

Prinsenberg, S. J., G. A. Fowler, A. van der Baaren, 1998. “Pack Ice Convergence Measurements by GPS-ARGOS Ice Beacons”, *Cold Regions Science and Technology*, 28, pp. 59-72.

-----------, A. van der Baaren, G. A. Fowler, and I. K. Peterson, 1997. “Pack Ice Stress and Convergence Measurements by Satellite-Tracked Ice Beacons”, in Oceans '97 MTS/IEEE Conference Proceedings, Vol. 2, pp. 1283-1289.

Seimac Ltd., 1998. “Ice Beacon Test Report”. Internal report by Seimac Ltd., Dartmouth, Nova Scotia, Canada, 12 p.

----------, 1995. The Seimac GPS/ARGOS Beacon. UM-230-99-006V1.0. Seimac Ltd., Dartmouth, Nova Scotia, Canada, i+14.

# 7 APPENDIX

This appendix contains a copy of a paper describing field results of an ice-tracking experiment using Seimac GPS beacons in 1995 off Labrador:  Prinsenberg, *et al.*, 1998.

ELSEVIER

Cold Regions Science and Technology 28 (1998) 59–72

cold regions
science
and technology

# Pack ice convergence measurements by GPS–ARGOS ice beacons

S.J. Prinsenberg *, G.A. Fowler, A. van der Baaren

*Department of Fisheries and Oceans, Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2*

Received 18 November 1996; accepted 2 August 1998

**Abstract**

Satellite-tracked ice beacons containing Global Position System (GPS) location sensors were field tested for their reliability and their position accuracy (both relative and absolute) before being deployed on the mobile pack ice to monitor pack ice motion. On flat lake ice, a single beacon on average provided hourly data 87% of the time with a position accuracy of 20 m. In ice rubble, data availability was reduced to 83% and position accuracy decreased to 35 m. Between pairs of beacons, relative distance accuracy depended on whether the positions of the beacons were derived using the same satellite constellation. For all available position data, the data availability for relative distances between beacons was 78% for the short 1-day data set of the lake ice site and 69% for the longer 25-day data set of the ice rubble site. Relative distance accuracies were respectively 15 and 20 m using all position data. When positions were derived using the same satellite constellation for beacon pairs, the data availability reduced to 60% for the lake site and 52% for the ice rubble site while the relative accuracy increased respectively to 1.5 m (lake) and 10 m (ice rubble). The beacons proved their durability by monitoring the ice motion for an additional 60 days in an offshore experiment in which three floes forming a triangle were tracked until the floes the beacons were on melted. 

*Keywords:* Pack ice; Convergence measurements; GPS–ARGOS ice beacons

## 1. Introduction

Efficient navigation along Canada's east coast is limited by insufficient information on the mobile pack ice which infests the area in the late winter and early spring. Of primary concern is the ice pressure due to pack ice convergence which reduces the maneuverability of ships and increase the risk of damage to ships and offshore structures. Satellite imagery techniques allow us to obtain a good picture of the distribution, concentration, convergence and divergence of the pack ice (Peterson and Prinsenberg, 1993). However to be most effective, remotely-sensed data must be complimented by in situ measurements to verify accurately ice divergence/convergence, ice pressure, ice thickness and surface roughness.

The magnitudes and spatial extents of ice convergence and divergence can be determined from ice drift circulation patterns determined from sequential satellite images. Although images provide a good large spatial coverage of ice drifts, their accuracy is poor relative to those derived by Global Position System (GPS) sensors mounted inside satellite-tracked ice beacons. Determining the reliability and

* Corresponding author. + 1-902-426-6929; Fax: + 1-902-426-2256; E-mail: sprinsen@bionet.bio.dfo.ca

0165-232X/98/$ - see front matter 
PII: S0165-232X(98)00013-5

accuracy of position data obtainable by satellite-tracked ice beacons for ice convergence and divergence studies is the topic of this manuscript.

During the winter of 1995, satellite-tracked ice beacons with GPS sensors were field tested for their reliability and accuracy, and used on offshore pack ice on the Labrador Shelf to monitor pack ice convergence and divergence. Other beacons being developed to monitor ice stress within an ice floe were also deployed. This manuscript reports on the results the GPS–ARGOS ice beacons. After describing the working components of the ice beacons, their reliability and accuracy in obtaining position data will be discussed for various surface conditions (land, level lake ice and rubble sea ice). Lastly, results of the offshore deployment of four beacons present their durability and ability to monitor the convergence and divergence of the mobile pack ice.

## 2. GPS–ARGOS ice beacon

The GPS–ARGOS beacon components are housed in a white fiberglass sealed hull and deployed with the narrow bottom section in a shallow ice hole (Fig. 1). The beacon, designed and built by Seimac of Dartmouth, Nova Scotia, Canada, weighs 65 lbs in its ice beacon configuration and is designed to sink after the ice floe it was deployed on melts to reduce ARGOS costs. The overall length is 95 cm with a narrow (10 cm diameter) bottom section in which the battery pack is housed (Fig. 2). The battery pack is capable of powering the internal components for at least 60 days at −35°C and 90 days at temperatures averaging −20°C (Seimac, 1995). The narrow battery section is deployed in a shallow 12 cm diameter ice hole to keep the beacon upright and the batteries isolated from the colder air temperatures. The nose cone of the beacon is painted black to absorb solar energy so that any snow and ice build-up will melt and not interfere with ARGOS and GPS data transmissions.

The major beacon components (Fig. 2) are the ARGOS PTT (Platform Transmitter Terminal) and antenna, a GPS sensor (Trimble CM-2) and GPS antenna (Trimble FOG), battery pack and magnetic activation switch. Once the beacon has been activated, the PTT will transmit every 90 s to the

Fig. 1. GPS–ARGOS beacon deployed on the offshore Labrador shelf pack ice.

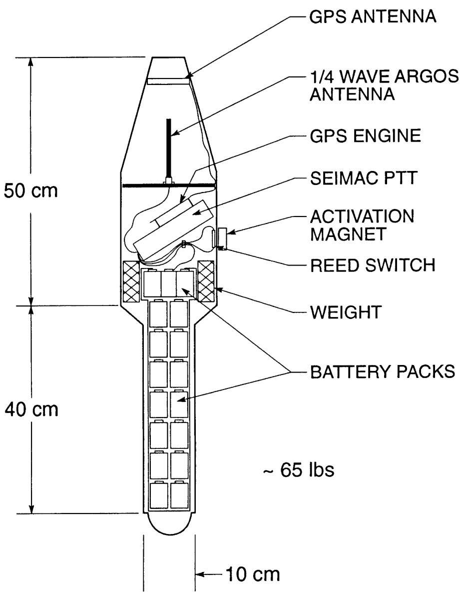


Fig. 2. Schematic of GPS–ARGOS beacon (redrawn from Seimac, 1995).

ARGOS satellite system. Transmissions can be monitored with a standard ARGOS PTT test set at the deployment site. Once the GPS has a valid position fix, the PTT internal clock will be synchronized to real GPS time. The GPS powers down unless it is within 5 min of the top of the hour. At 5 min to the hour, the GPS will power up and will sent a navigation message every 5 s to the PTT. The last message before the hour will be stored in an array and a new message will be calculated for the transmission by the PTT. All beacons log their position and the satellite constellation used to derive their position on the hour ($\pm 5$ s). The array stores the eight most recent positions along with their satellite constellations. After each hourly fix the PTT internal clock is re-synchronized and a new ARGOS message is compiled and transmitted. The transmission consists of two, 32 byte messages, one containing the four most recent position and constellation data, the other containing the four older position and constellation data. Each message consists of one absolute position and three relative positions. The two messages are transmitted interleaved, i.e., alternating between the two messages with each transmission. Upon activation, the beacon transmits a single message until the fifth GPS position is obtained. Battery voltage is also transmitted.

## 3. Stationary tests

Stationary tests were conducted using six beacons at four different sites to determine the beacons' reliability and position accuracy. The first site was an open grass 'field' near the Bedford Institute surrounded by buildings, the second on the Seimac (manufacturer) 'roof'; both these sites were in Dartmouth, Nova Scotia. The third and fourth sites were in Labrador at 54.5°N latitude; one site was on a flat

Table 1
Statistical analysis for single beacon position relative to its mean position

| Site | Direction component | Beacons/h | RMS (m) deviations | | Data availability (%) | |
|---|---|---|---|---|---|---|
| | | | Range | Mean | Range | Mean |
| Field | N | 5/259 | 28–37 | 31.1 | 65–88 | 84.0 |
| | E | 5/259 | 24–32 | 25.8 | 65–88 | 84.0 |
| Roof | N | 5/134 | 23–39 | 30.5 | 48–85 | 76.2 |
| | E | 5/134 | 20–28 | 23.5 | 48–85 | 76.2 |
| Lake-1 | N | 4/22 | 19–29 | 24.8 | 77–91 | 87.0 |
| | E | 4/22 | 19–35 | 25.7 | 77–91 | 87.0 |
| Lake-2 | N | 5/17 | 18–23 | 20.8 | 76–100 | 87.2 |
| | E | 5/17 | 16–19 | 17.1 | 76–100 | 87.2 |
| Coastal | N | 4/621 | 25–33 | 28.6 | 81–85 | 83.0 |
| Ice | E | 4/621 | 23–24 | 23.9 | 81–85 | 83.0 |

Table 2
Statistical analysis of the distance between all possible beacon pairs for the case when positions are derived using all satellite constellations

| Site | Direction component | Beacons/h | RMS (m) deviations | | Data availability (%) | |
|---|---|---|---|---|---|---|
| | | | Range | Mean | Range | Mean |
| Field | N | 5/259 | 20–36 | 26.0 | 55–79 | 66.2 |
| | E | 5/259 | 15–32 | 23.5 | 55–79 | 66.2 |
| Roof | N | 5/134 | 16–49 | 28.8 | 36–72 | 55.4 |
| | E | 5/134 | 15–32 | 21.4 | 36–72 | 55.4 |
| Lake-1 | N | 4/22 | 5–22 | 14.6 | 68–86 | 77.2 |
| | E | 4/22 | 10–25 | 16.1 | 68–86 | 77.2 |
| Lake-2 | N | 5/17 | 1.6–8 | 4.9 | 65–94 | 79.3 |
| | E | 5/17 | 5.3–14 | 11.8 | 65–94 | 79.3 |
| Coastal | N | 4/621 | 10–20 | 15.1 | 66–72 | 69.2 |
| Ice | E | 4/621 | 11–36 | 25.3 | 66–72 | 69.2 |

surface of 'lake' ice covered with 1 m of snow (Lake Melville, Labrador) and another site was within a rubble field of 'coastal sea ice' along the mid Labrador coast. Two short tests were done at the 'lake' site; for one test (lake-1) the beacons were on 1 m stilts to improve their view of the horizon while for the second test (lake-2) the beacons were deployed directly into the snow layer.

Results of these four tests are summarized in Tables 1–3. Each table lists the statistical analysis of the data available for each trial. The first column gives the site of the trial. Column 2 gives the position component (N/E) for the data in the following columns. Column 3 gives the number of beacons in the trial and how many hours the trial lasted. Column 4 gives the range of the RMS deviation around the median position for the group of beacons in the trial and column 5 gives the mean of the RMS deviation for all the beacons in the trial. Column 6 gives the range of the percentage data availability for the group in the trial while column 7 gives the mean percentage data availability for the entire test group. For example: The first test was in the field in which 5 beacons reported position data for 259 h. The North position varied from 28–37 m around each beacon mean position and provided a group mean of 31.1 m. The East position varied between 24 and 32 m and had a mean of 25.8 m. The percentage data availability of the beacons ranged from 65 to 88% and had a mean for the 5 beacons of 84%. Table 1 provides us with a look at the individual beacon positions. Table 2 provides us with a look at the

Table 3
Statistical analysis of the distance between all possible beacon pairs for the case when positions are derived using just the same satellite constellation

| Site | Direction component | Beacons/h | RMS (m) deviations | | Data availability (%) | |
|---|---|---|---|---|---|---|
| | | | Range | Mean | Range | Mean |
| Field | N | 5/259 | 8–26 | 16.3 | 33–51 | 40.5 |
| | E | 5/259 | 7–23 | 13.3 | 33–51 | 40.5 |
| Roof | N | 5/134 | 1.2–26 | 11.8 | 6–42 | 22.1 |
| | E | 5/134 | 1.2–13 | 6.2 | 6–42 | 22.1 |
| Lake-1 | N | 4/22 | 1.1–3.1 | 1.8 | 29–52 | 38.5 |
| | E | 4/22 | 0.9–3.3 | 2.1 | 29–52 | 38.5 |
| Lake-2 | N | 5/17 | 1.0–2.4 | 1.4 | 41–82 | 60.1 |
| | E | 5/17 | 0.6–1.3 | 1.0 | 41–82 | 60.1 |
| Coastal | N | 4/621 | 2.9–11 | 6.2 | 46–57 | 52.2 |
| Ice | E | 4/621 | 1.7–23 | 10.5 | 46–57 | 52.2 |

statistical data between beacon pairs using all available data. Table 3, in contrast, just looks at the beacon pairs when their position data is derived from the same satellite constellation.

For a single beacon (Table 1), the east component in most cases was more accurate than the north component probably either due to the fact that the satellite orbits run nearly north–south or because positions are stored in units of degrees and one degree north latitude accounts for twice the distance as one degree west longitude. The availability of data did not vary between sites for beacons that did

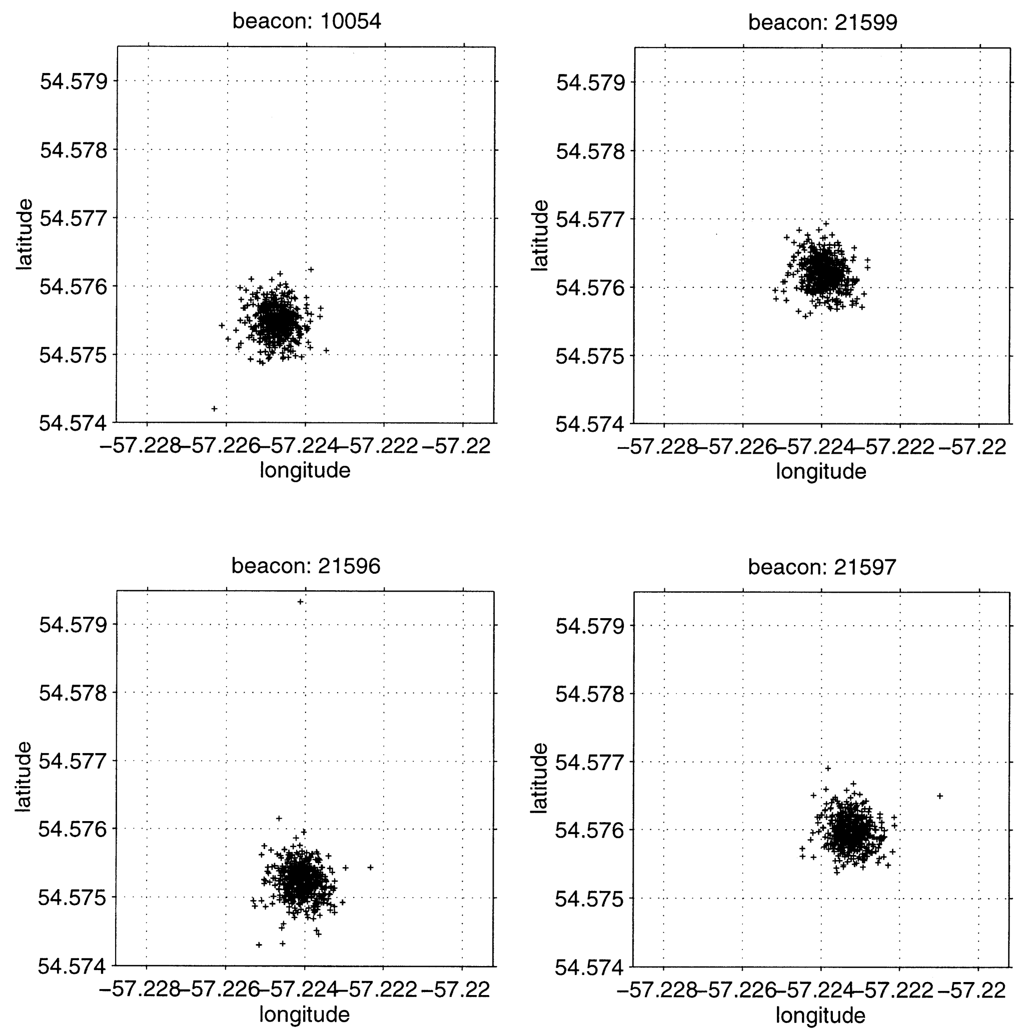


Fig. 3. Scatter plots of hourly position data from four GPS–ARGOS beacons forming a 100 m × 100 m square in the coastal land-fast ice rubble.

report. The best results were from the lake-2 ice site when the beacons were directly put into the snow layer. For this case the RMS absolute position accuracy was 17.1 m for the east/west component and 20.8 m for the north/south component.

The data availability (Table 2) for beacon pairs reduced by 15 to 20% relative to those of single beacons (Table 1). The means of the RMS of deviations in the relative distances between beacon pairs also improved (reduced) to 5–15 m for the lake site,

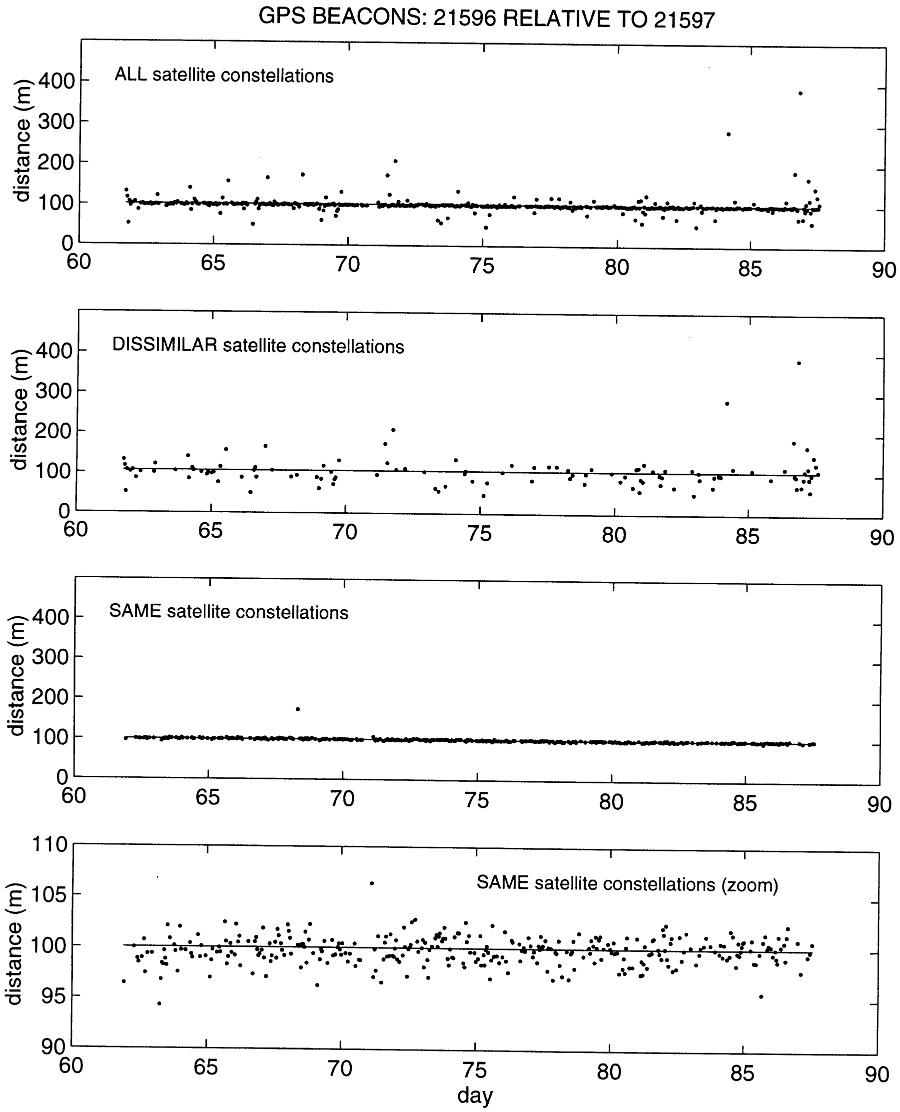


Fig. 4. Relative distance time series between beacons forming the southern corners of the 100 m × 100 m square.

15–25 m for the coastal site and to 21–29 m for the field and roof sites. The lake-2 test, with beacons directly in the snow layer, provided the best results. While beacons were designed for this type of deployment; it was thought that putting them up on stilts might provide a better view over ice rubble. However, the beacons appear to see multiple reflections from the ice surface which reduced their position accuracy. When relative distances between beacon pairs were determined for beacon pairs seeing the same satellite constellation (Table 3), the percentage of data availability reduced further but the

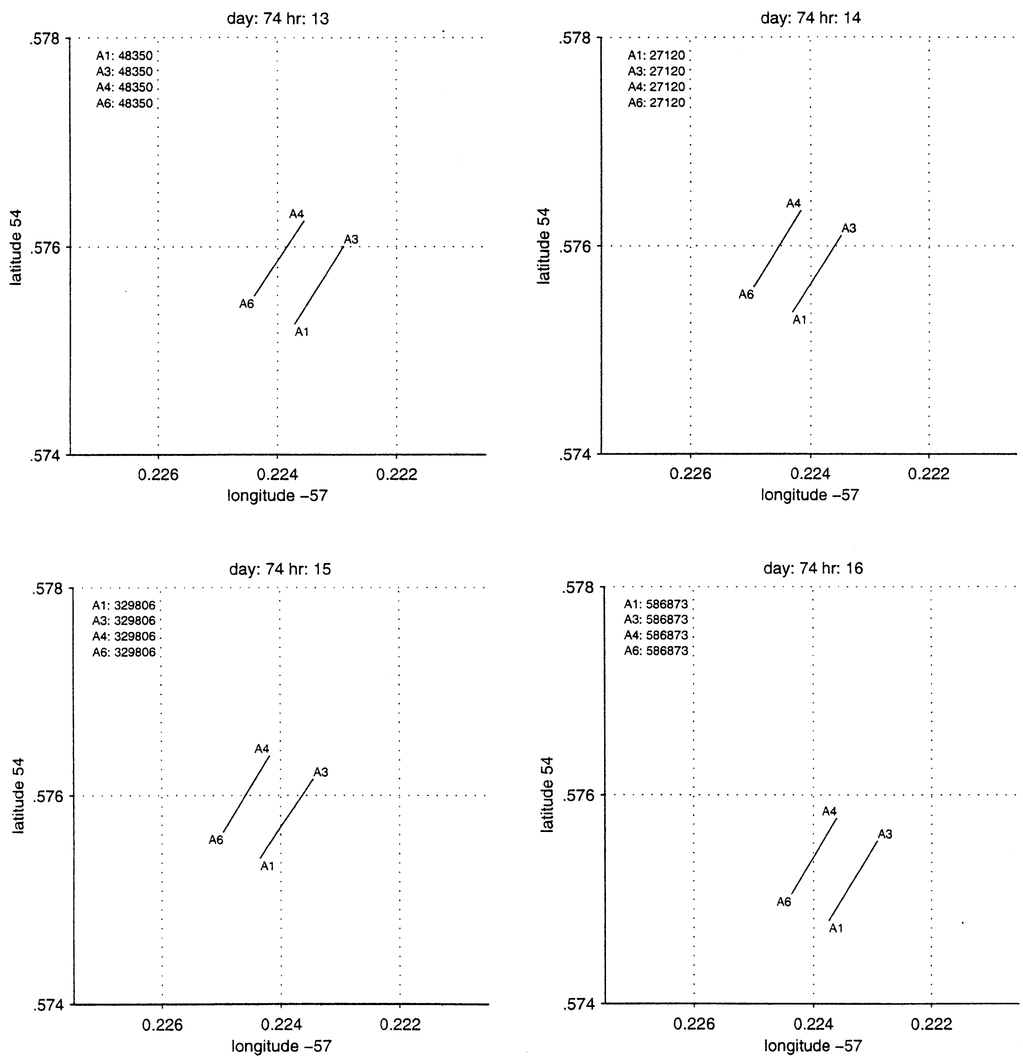


Fig. 5. Four consecutive snap shots showing the four corners of the square with positions derived from same satellite constellations.

relative distance accuracy between beacons increased for all sites. For the lake sites the RMS deviations in the relative distances ranged between 0.6 and 3.3 m with means ranging between 1.0 and 2.0 m. For the coastal ice (beacons on 1 m stilts) multiple reflections from the ice surface caused large deviations. The RMS deviations ranged from 1.7 to 23 m with means of 6.2 to 10.5 m, smaller than those when all satellite fixes were used (Table 2) but not as small as lake sites when just fixes from same satellite constellation were used (Table 1). Note that the data set of the coastal site is 30 to 40 times longer than those of

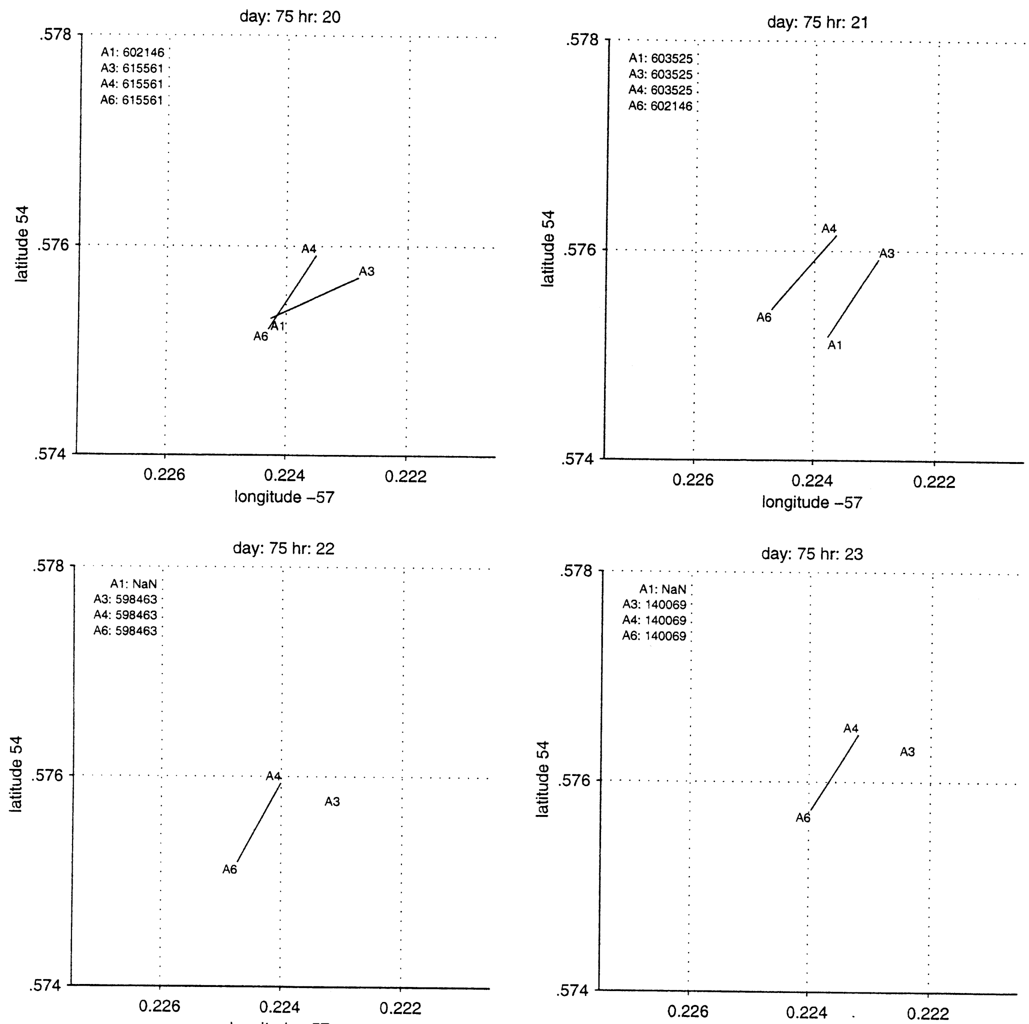


Fig. 6. Four consecutive snap shots of corners of the square when dissimilar satellite constellations are used for position fixes or when data is missing.

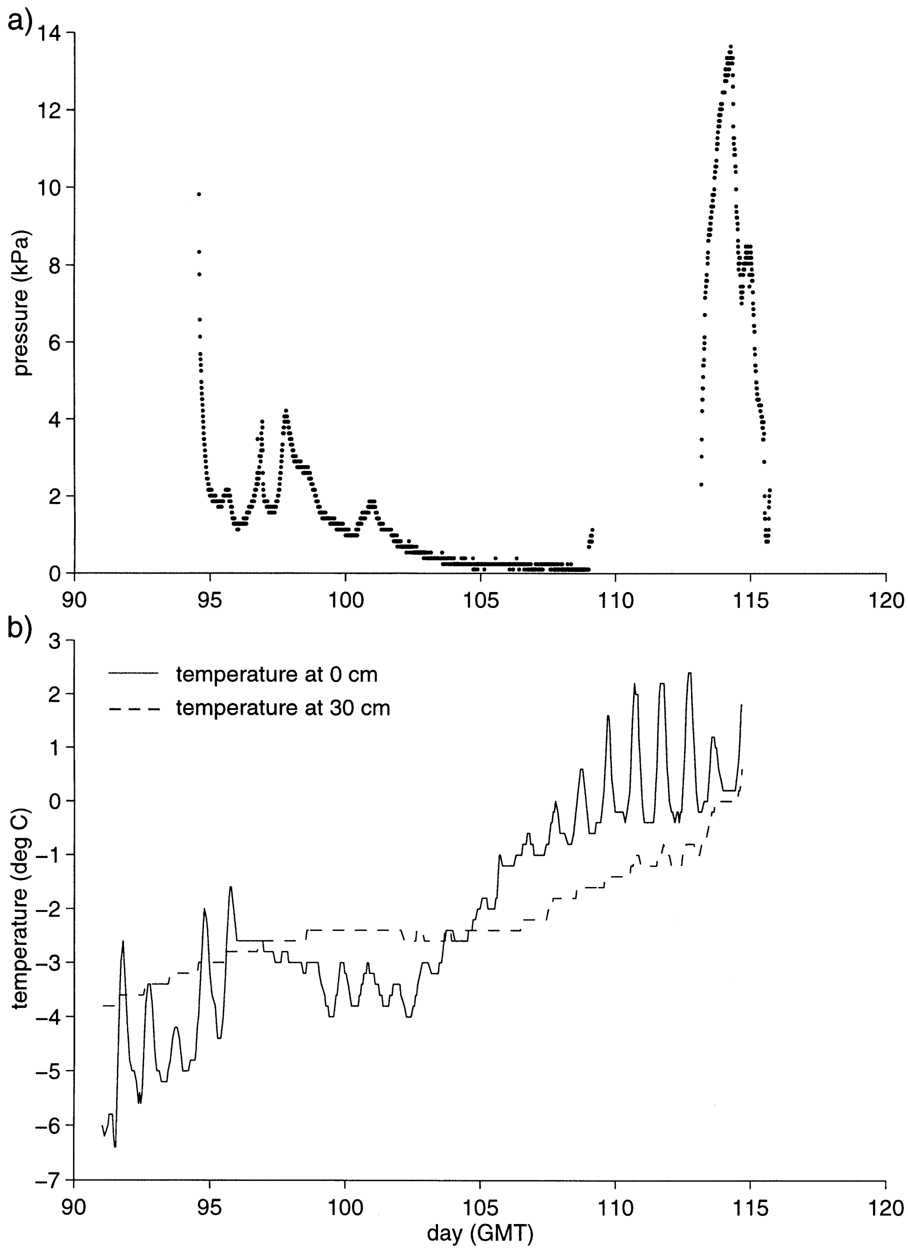


Fig. 7. Time series of ice pressure, ice temperature (30 cm) and ice/air interface temperature (0 cm) from the middle of a 250 m × 200 m ice floe, 60 cm thick.

the lake sites and does provide a better confidence limit.

Fig. 3 shows scatter plots of the actual positions of the four beacons from the coastal ice rubble used in the statistics of Tables 1–3. They were located at the corners of a 100 m by 100 m square and show each a very tight radial pattern caused by the GPS in its Selective Availability (SA) mode. Most positions for each beacon fall within a 100 m (0.001° Latitude) diameter circle. The time series of the relative distances between the two beacons along the southern side are shown in Fig. 4. The top panel shows all the available relative distances, while the next two panels show those relative distances from positions de-

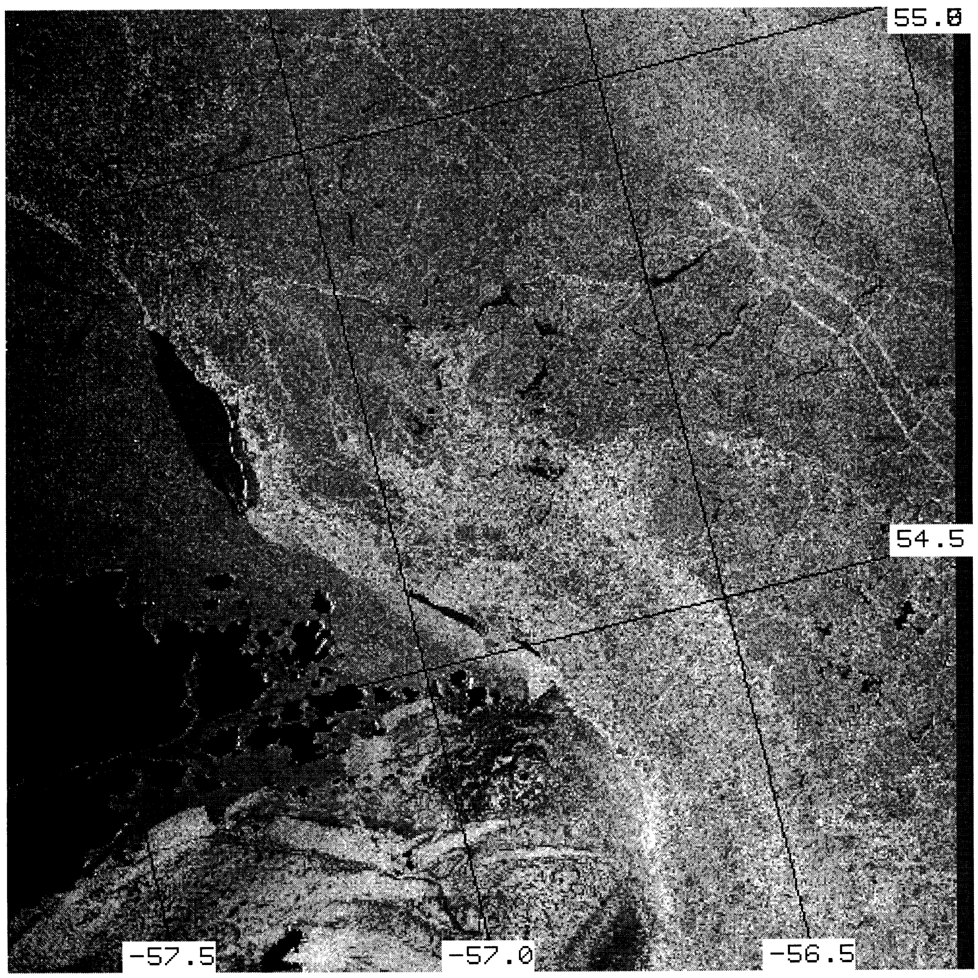


Fig. 8. ERS-1 (100 km × 100 km) SAR image of April 12, 1995. Position of the beacons is shown by the small triangle located inside the offshore shear zone on the far left side of the image.

termined respectively from dissimilar and of similar satellite constellations. Ignoring the distances from dissimilar satellite constellation provide a very accurate relative hourly distance time series with a data availability of around 50%. For the case shown, one data point at Julian day 68 appears to be in error and was ignored in the finer scale plot (bottom panel). For the plots shown the RMS of distance deviation of the total time series (71% of possible data) is 21.6 m (top panel) reducing to 1.3 m (52% of data) for the third panel when the data point at day 68 was omitted.

Figs. 5 and 6 show two examples of the position data from the coastal ice rubble site as plotted as four consecutive snap shots showing each of the four corner positions (when available) of the 100 m by

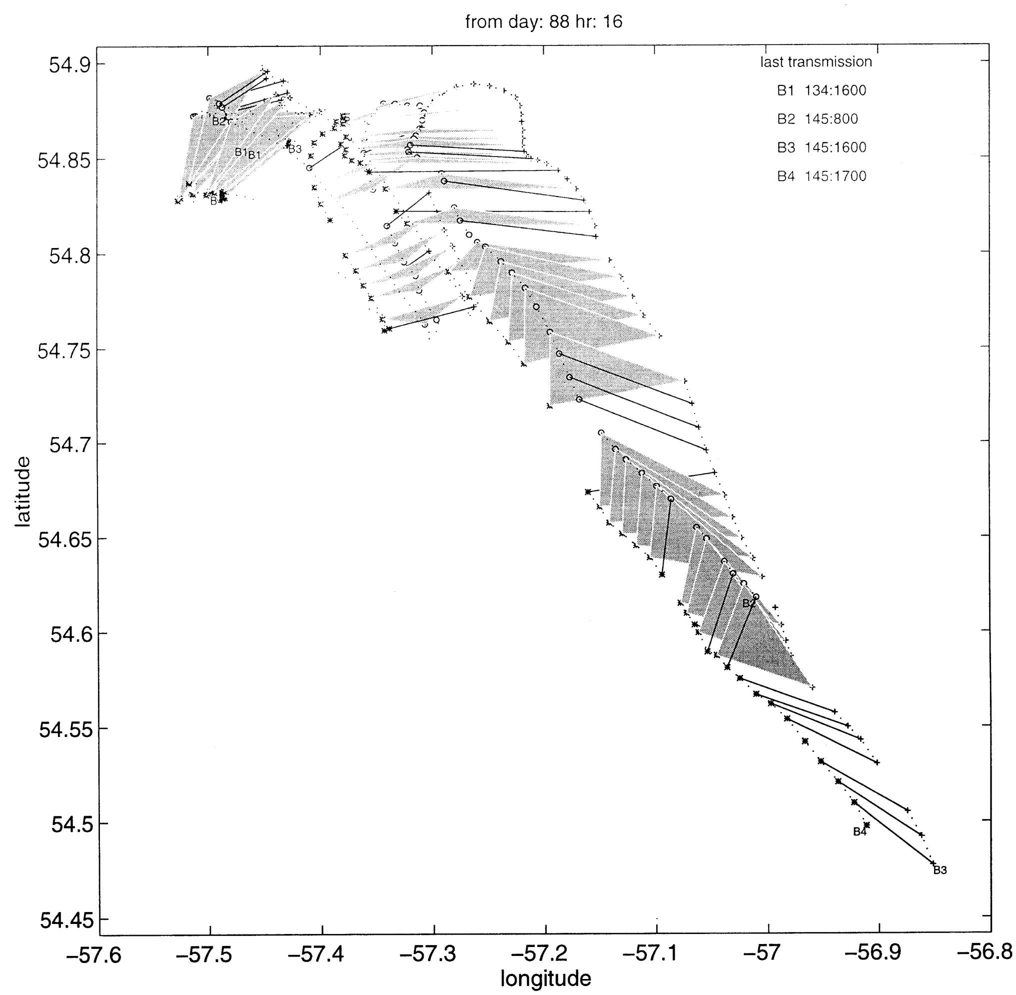


Fig. 9. Trajectory of triangle formed by the beacons at every 6 h intervals.

100 m square. Fig. 5 is an example of 'good' data when the beacon positions of each of the four consecutive hourly scenes were determined using the same satellite constellation. In contrast, Fig. 6 is an example of 'bad' data when the beacons either had data missing or did not see the same satellite constellation as represented by a six digit number (see insert) listing consecutively 3 two-digit satellite

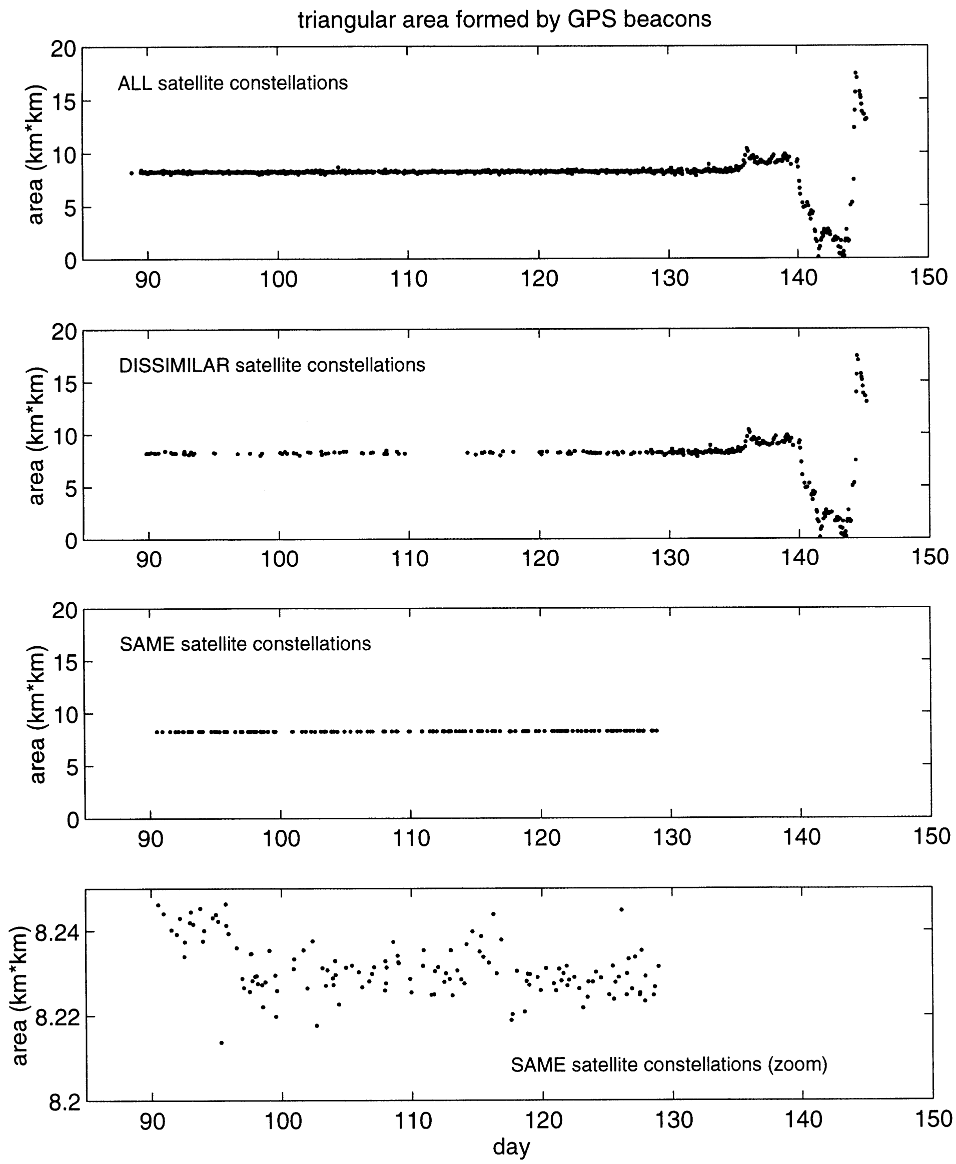


Fig. 10. Time series of area change of the triangle for just same satellite or all satellite constellations.

numbers used by the beacons to determine their position.

## 4. Pack ice motion

On March 27 (day 88), the beacons were redeployed on the offshore pack ice to monitor ice divergence within a triangle with approximately 4 km, 4 km and 3 km long sides. At the centre of the triangle the ice pressure and location were also monitored, but these beacons stopped reporting on May 15 (day 115), before the GPS/ARGOS beacons started to move on day 135. Pressure data recorded up to this date (Fig. 7) by an uni-directional stress sensor at a depth of 30 cm in a 60 cm thick ice floe did not measure much ice stress possible due to the soft ice and warm air conditions. The ice stress beacon, ice temperature staff beacon and location beacon at the centre of the triangle all stopped recording data on day 115 suggesting that the floe they were on was destroyed by ice ridging. The beacons forming the corners of the triangle remained nearly stationary until day 135 indicating that part of the pack ice at this location was temporarily land fast. An ERS-1 SAR picture of the area from April 12 (Fig. 8) confirms this; the triangle formed by the beacons is inside the offshore shear zone demarking mobile offshore pack ice (brighter area on SAR image) from the temporarily land-locked pack ice inshore (darker area on SAR image). Tracks made by small ice bergs moving through the land-locked pack ice in 50 m water depth in the vicinity of the beacons are not visible on the SAR image although clearly identifiable from the air by helicopter. On the other hand, tracks made by larger grounded ice bergs in 150 m water depth are clearly visible in the SAR image. Two bergs grounded at $-56.4$ W and 54.9 N on the right side of the image made parallel tracks of ice rubble (bright on image) as the pack ice moved past the bergs. A third berg is also identifiable through its rubble track at the top centre of the image also at a location where water depth is 150 m.

After day 135 the bottom side of the triangle by the beacons lengthened (Fig. 9), increasing the triangle's area (Fig. 10) as the triangle moved slightly northwestwards. Afterwards the area decreased as the triangle height decreased while moving southeastwards. The apex of the triangle continued to move faster southwards forming now a small upside down triangle (end of day 142). By the middle of day 143 the triangle was reduced to a 7.5 km straight line while moving northwards. After day 143 the beacons moved quickly southeastwards, the normal mean drift direction for the offshore pack ice (Fig. 9). The beacons again formed a right side up triangle. Its area first increased beyond that of the original size before it decreased when the two inshore beacons caught up to the offshore beacon (Fig. 10). The accuracy of the change in triangle area depends on the determination of the beacons' locations. When locations of all three beacons are derived from GPS fixes using the same satellites the area error for the $4 \times 4 \times 3$ km triangle (8.25 km$^2$) would be 0.25% for a distance inaccuracy of $\pm 2$ m and increases to 2.5% for a distance error of $\pm 20$ m when dissimilar satellites were used for the GPS fixes. After day 129, the beacons positions forming the triangle were for some unknown reason never determined from the same satellites even though at times they were closer together than prior to day 129 when 50% of the time their locations were determined from similar satellites. Ridging within the pack ice probably altered the beacons view of the sky but further tests determining the effect of the atmospheric conditions on the ice beacons' performance are also required.

## 5. Conclusion

The GPS–ARGOS beacons tested do provide an order of magnitude better position accuracy ($\pm 20$ m) than just the ARGOS location ($\pm 200$ m). Relative distance accuracies between beacon pairs can achieve values of 1–2 m when the locations of the beacons are determined by the same satellite constellation. However, the data availability for beacons determining their position from the same satellite constellation is around 50% under the best conditions, and appears to diminish, possibly due to rafting within the pack ice or spring atmospheric conditions. The battery packs of the beacons tested provided power for the 25 day ice rubble test and 60 day pack ice motion experiment.

## Acknowledgements

The research described was funded through the Federal Panel on Energy Research and Development and supported by the Department of Fisheries and Oceans Canada. D. Belliveau and D. Lawrence provided helpful comments on the original draft of the manuscript. The helicopter pilots of Universal Helicopters and Canadian Helicopters, based in Goose Bay, eagerly assisted in the field work and were a pleasure to work with. The authors would like to acknowledge the reviewers' and pilots' valuable contribution.

## References

Seimac, 1995. The Seimac GPS/ARGOS beacon. UM-230-99-006V1.0. Seimac, Dartmouth, Nova Scotia, Canada, i + 14 pp.

Peterson, I.K., Prinsenberg, S.J., 1993. Ice drift of Newfoundland, derived from AVHRR Imagery and ice beacons. 16th Canadian Symposium on Remote Sensing, Sherbrooke, Quebec, Canada, pp. 227–232.