ACCIDENT INVESTIGATION BOARD FINLAND

Investigation report

B 2/2000 M

ms FINNFELLOW, grounding near Överö in Aland, April 2, 2000

This investigation report was written to improve safety and prevent new accidents. The report does not address the possible responsibility or liability caused by the accident. The investigation report should not be used for purposes other than the improvement of safety.

Onnettomuustutkintakeskus
Centralen för undersökning av olyckor
Accident Investigation Board Finland

Osoite / Address:	Yrjönkatu 36 FIN-00100 HELSINKI	Adress:	Georgsgatan 36 00100 HELSINGFORS

Puhelin / Telefon: (09) 1825 7643
Telephone: +358 9 1825 7643

Fax: (09) 1825 7811
Fax: +358 9 1825 7811

Sähköposti: onnettomuustutkinta@om.fi tai etunimi.sukunimi@om.fi
E-post: onnettomuustutkinta@om.fi eller förnamn.släktnamn@om.fi
Email: onnettomuustutkinta@om.fi or forename.surname@om.fi

Internet: www.onnettomuustutkinta.fi

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TO THE READER

Investigation of accidents in waterborne traffic. In Finland the Accident Investigation Board investigates all waterborne traffic accidents that have occurred:

- in Finland's territorial waters or
- in which a Finnish vessel has been involved.
- In addition, incidents in waterborne traffic can also be investigated.

An accident in which a leisure boat has been involved will only be investigated if the investigation is considered useful for improving safety and preventing new accidents.

The statutory basis of accident investigation in Finland is the Accident Investigation Act (373/1985) and the Accident Investigation Degree (79/1996). The investigations are carried out in accordance with the principles stated in the IMO Code for the investigation of maritime casualties and incidents, agreed upon in resolutions A.849(20) and A.884(21) as well as in EU directive 1999/35/EC on a system of mandatory surveys for the safe operation of regular ro-ro ferry and high speed passenger craft services. In the reporting of accident investigations, the Accident Investigation Board follows an established form and the investigations are published either in separate publications or in the publication series *"Maritime accidents and incidents"* as well as at the internet address: http://www.onnettomuustutkinta.fi.

The investigation report contained in this publication is:

B 2/2000 M ms FINNFELLOW, grounding near Överö in Aland, April 2, 2000

Helsinki November 27, 2001

SUMMARY

The Finnish-flagged passenger ferry ms FINNFELLOW grounded on her way from Kappelskär to Naantali at 02:32 on 2 April 2000 on the north shore of Föglö in the Aland archipelago. There were 81 people on board, 58 of whom were passengers. The vessel ran aground at a speed of about 14 knots as a result of a gyrocompass malfunction. The grounding was soft and damage was limited to the vessel's bow-thruster compartment and a few of the bottom tanks adjacent to it. No oil leaks occurred.

The FINNFELLOW was constructed in 1973 but her steering system had been renewed a few years before the grounding. In addition, a modern integrated navigation system and two gyrocompasses had been installed on the bridge.

The voyage had proceeded normally. Visibility was good, the night was dark and the speed of the northerly wind was approximately 15 m/s. Three men were manning the bridge: the watch officer, the company pilot and the lookout. The pilot was steering the vessel on autopilot. In the cockpit there are two radars, plus seating, located side by side forming part of the vessel's navigation system; the pilot was in the right-hand seat navigating and the watch officer was in the left-hand seat monitoring activity.

The events that led to the grounding occurred when the vessel was nearing the end of a turn to starboard. During the turn, when only 2.5 degrees remained of a 50-degree change of heading, the gyrocompass jammed at the same reading for 66 seconds. When the vessel grounded, the autopilot was set to its heading mode in which the vessel's turn radius is predetermined.

Because the autopilot received incorrect heading information, indicating that the vessel had not yet turned to the desired course, it started to turn the vessel to starboard by gradually increasing the rudder angle. The bridge personnel were not immediately aware of this unplanned turn off the fairway. Factors contributing to their lack of awareness included the slowing of the vessel's rate of turn, the absence of alarms, and the dark night in which only a few of the lights marking the fairway were visible. The watch officer only realised that the vessel was turning to starboard about 30 seconds after the gyrocompass jammed. A turn to port and a reduction in speed were effected immediately, but they did not have the desired effect and the FINNFELLOW grounded 85 seconds after the gyrocompass malfunction.

During the investigation it was established that the immediate cause of the gyro fault was radio frequency interference. The exact frequency of the interference, and how it entered the system to pass to the compass, could not be determined. It was also observed that the safety systems designed to prevent a heading error from affecting the navigation system had failed. The conventional compass system based on the IMO declaration A.424(XI) was not sufficiently reliable to act as the only sensor providing the heading. The conventional compass system is vulnerable as it stands; this is why the investigation board recommends that the actual navigation system be further protected, and that there are additional heading references to act in parallel with those from the gyrocompass.

INDEX

LIST OF ABBREVIATIONS

ANS	Advanced Navigation Software
ARPA	Automatic Radar Plotting Aid
CHL	Curved Headline, turning plan of autopilot on screen of ATLAS radar
COG	Course Over Ground
COURSE MODE	Steering mode of TRACKPILOT autopilot where heading commands refer to course over ground
DGPS	Differential Global Position System
DGPS CMG	DGPS course measured over ground
DGPS SMG	DGPS speed measured over ground
FMEA	Failure Mode and Effect Analysis
FU	Follow-Up
HDG	Compass Heading
HEAD-UP	Radar display mode without compass stabilisation
HEADING MODE	Steering mode of TRACKPILOT where heading commands refer to compass heading over water
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISM Code	International Safety Management Code
ISO	International Organization for Standardization
LOG BT	Bottom Track, motion relative to bottom
MRCC	Marine Rescue Co-ordination Center
MTBF	Mean Time Between Failures
NACOS	Navigation and Command System
NCC	Navigation Command Console
NEXT	Heading of programmed course between two successive way points
NMEA	National Marine Electronics Association
OOW	Officer Of the Watch
PREDICTOR	Prediction of motion of vessel on radar
RADIUS	Turning radius used by autopilot
SOG	Speed Over Ground
SOLAS	Safety of Life at Sea Convention
STEP connection	Heading information in step form
TMC	Transmitting Magnetic Compass

TRACK	Heading of programmed course at location of vessel between two successive waypoints
TRACKPILOT	Type name of NACOS autopilot
TRACK MODE	Steering mode of TRACKPILOT autopilot which follows a pre-set course
UHF	Decimetric waves, Ultra High Frequency
UTC	Coordinated Universal Time
VHF	Metric waves, Very High Frequency
VTS	Vessel Traffic Service
WP	Waypoint
XTD R or L	Cross Track Distance in meters to left or right

Figure 1. ms FINNFELLOW after refloating on 5 April 2000.

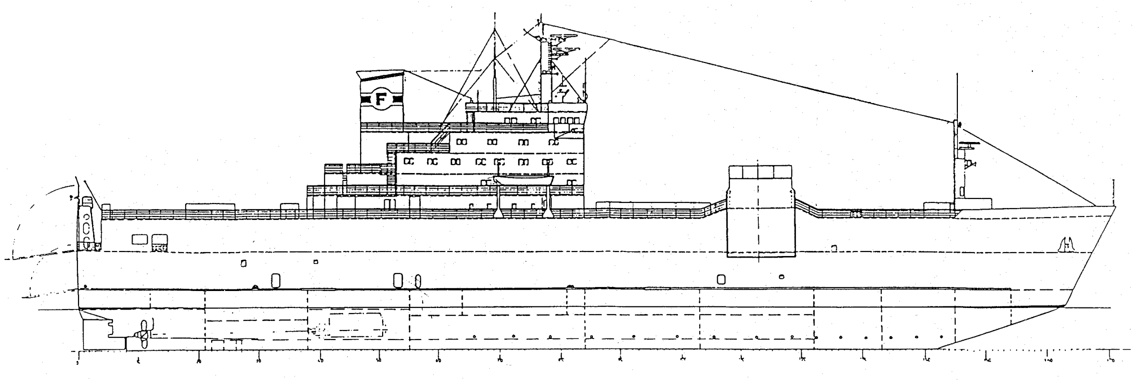


FIgure 2. General arrangement of ms FINNFELLOW.

1 GENERAL DESCRIPTION AND INVESTIGATION OF THE ACCIDENT

Information about the vessel, the voyage and the rescue operation are based on the following: the maritime declaration and its appendices, the rescue authorities' journals, and the crew interviews conducted by the investigation board.

1.1 The vessel and crew

1.1.1 General data

Name of the ship	ms FINNFELLOW
Home port	Helsinki
Identification	OIBS
IMO code	7315143
Type	Ro-ro passenger vessel / cargo ferry / train ferry
Nationality	Finnish
Year of construction	1973 / Turku
Length	137.34 m
Width	24.57 m
Draught	6.12 m
Capacity (dead weight)	4922 t
Machine power	2 x 5149 kW
Speed	19.3 knots

The vessel has two controllable-pitch propellors and one rudder.

1.1.2 Crew

The manning certificate dated 6 September 1999 (valid until 6 September 2004) stipulates a crew of 15. During the voyage the vessel carried a crew of 21, plus 2 trainees and 58 passengers.

At the time of the accident, the bridge watch consisted of the officer of the watch, the pilot and the lookout. The officer of the watch was monitoring activity, the pilot was navigating, and the lookout was keeping a visual lookout. The officer of the watch and the pilot were sea captains and both had piloting qualifications. In addition, in 1997 both men had received special training on the integrated navigation system fitted to the FINNFELLOW. They also had several years' experience of the vessel and of her route. The officer of the watch had served as mate on the vessel since 23 July 1996, the pilot had commenced piloting on 24 November 1997 and the seaman who was the lookout had been a seaman since 18 January 1990.

1.1.3 The cockpit and its equipment

Figure 3. Integrated navigation and steering console of ms FINNFELLOW.

Integrated Navigation System	ATLAS NACOS 25-2
S-band, 10 cm marine radar	ATLAS 9600 ARPA, 2 radars
X-band, 3 cm marine radar	ATLAS 9600 ARPA, 1 radar
DGPS positioning receiver	TRIMBLE DSM PRO
DGPS positioning receiver	MAGNAVOX MX 200
Gyro compass	RAYTHEON (ANSCHÜTZ) STANDARD 20, 2 compasses
Heading Deviation Alarm	RAYTHEON (ANSCHÜTZ)
Course Plotter	IDE 3200
Magnetic Compass	Krohn & Sons (not connected to NACOS)
Autopilot	ATLAS TRACKPILOT
Depth sound	SIMRAD
Speed and distance measuring	ATLAS DOLOG 22 doppler
Electronic chart	Advanced Navigation Software, ANS
Wind gauge	THIES

1.2 Accident events

1.2.1 Weather conditions

The weather in the region of the accident was cloudy with good visibility. The wind blew from N/NNE averaging 15 m/s. According to the officer of the watch, the following wind speeds had been observed during the voyage: Ledfjärden 16-18 m/s, Prästskär 12 m/s, Hjulgrund 17 m/s, and Skarpskär 12-14 m/s.

About an hour after the accident, ms AMORELLA reported a northerly wind speed of 17 m/s at the lead into Nötö. The waves in the archipelago were small.

1.2.2 The voyage

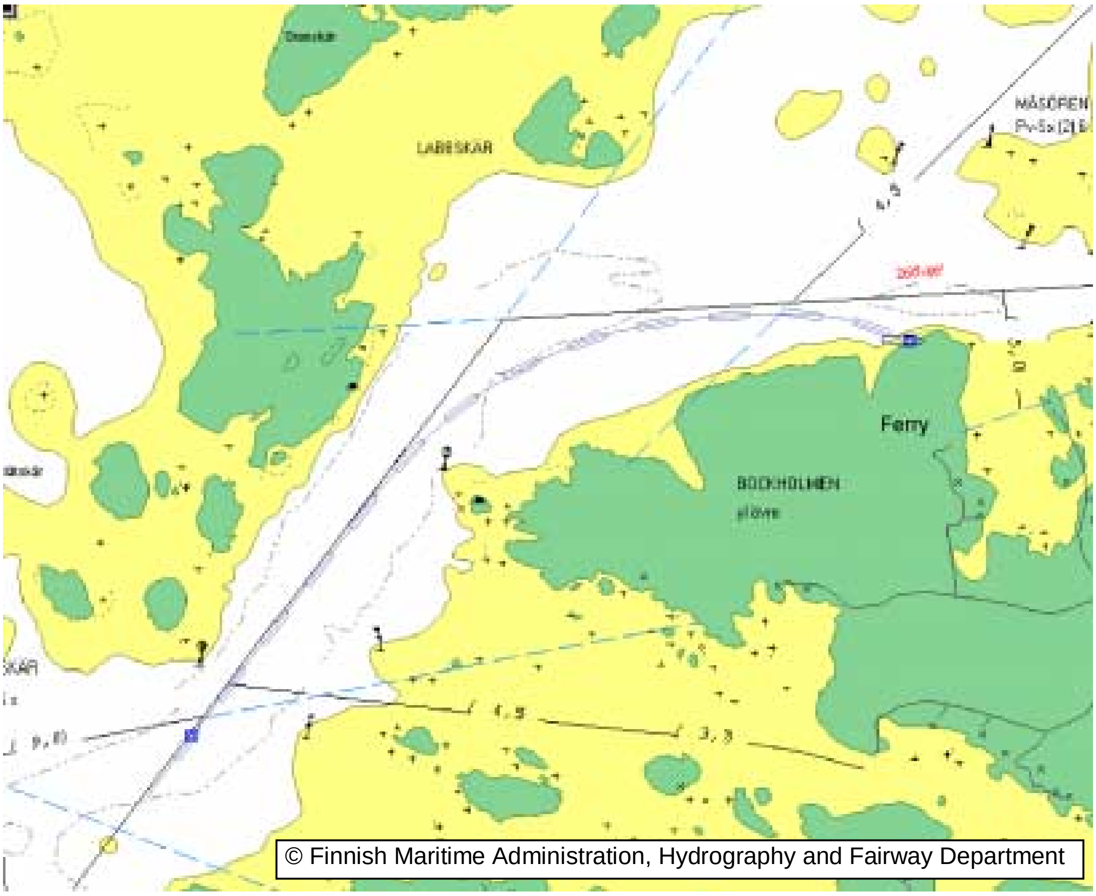


Figure 4 Reconstructed grounding of ms FINNFELLOW based on data registered on board.

The FINNFELLOW was on her regular route from Kapellskär in Sweden to Naantali in Finland on 2 April 2000. According to the vessel's log, the vessel had departed from Kapellskär at 23:10 the previous night and had passed Hjulgrundet at 02:12.

At the time of the accident there were three men on the bridge: the officer of the watch (OOW), the pilot and the lookout. The officer of the watch was monitoring activity from the left-hand seat of the command console, the pilot was navigating using the autopilot from the right-hand seat of the command console, and the lookout was keeping a visual lookout.

When the vessel was approaching the Skarpskär bend (Figure 4), both true motion radars were in use. The left radar was set to a scale of 1.5 miles and the right to 0.75 miles. Both radar trails were switched off. The vessel motion predictor was in use on both radars and also on the ANS chart. The NACOS autopilot was set to its HEADING mode. Gyro number 1 was the selected compass giving the heading and the Trimble DGPS was active. The vessel was travelling at full speed (about 16 knots).

No oncoming traffic was met at the Skarpskär bend. It was agreed that the next incoming vessel, the FINNARROW, would be met at the Delet open area.

The Skarpskär turn had been initiated later than normal to offset the effect of the wind, and a heading of 85° had been selected as the next heading (instead of 86° according to the passage plan). The FINNFELLOW normally turns gently in the turns. During the turn, the officers of the watch monitored the 'course over ground' on the NACOS screen to detect any drift. This is done particularly when steering in the HEADING mode.

During the turn, the leading lights of the following lead were visually checked. The lights were plainly visible and they were all functioning. Towards the end of the turn the NACOS screen showed that the FINNFELLOW was 10-12 metres starboard of her planned route. The vessel's programmed course followed the centre line of the fairway. From observation of the leading lights and the markers above the radar screen and on the window, it was seen that the vessel's heading pointed to port of the lights.

The officer of the watch noticed on the NACOS screen that the lateral distance to the track had increased to 15-16 metres. He also noticed that the heading had slid to starboard of the leading lights and that the radar chart did not match the echoes. The radar echoes then began to turn anticlockwise and the image became fuzzy. The radar motion predictor was still pointing directly ahead. The officer of the watch told the pilot to switch to manual steering. He realised that the rudder angle was 20 degrees to starboard and increasing. The rudder was full to starboard when the pilot switched to manual steering and turned hard to port.

Immediately after his command the officer of the watch tried to switch over to the other gyro, but he was unable to do so because the gyro alarm had activated (it is not possible to switch gyros until the alarm has been acknowledged). Simultaneously the pilot said that the ship will strand. The OOW moved over to the engine controls (see Figure 7). He zeroed the port engine to slow down the turning. The vessel was still turning slowly to starboard. The Överö harbour lights were about 20 degrees to port of the vessel's bow. The turning ceased and the OOW noticed that the stranding was inevitable. He reversed both engines to the 'full astern' position. The vessel began to turn slowly to port but he realised that this action was too late. Prior to the impact, the vessel had turned about 10-15 degrees to port.

The officer of the watch alerted everyone on the bridge that the vessel was about to impact with the shore. The vessel's speed had dropped to about 14 knots. The FINNFELLOW ran aground on the north shore of Bockholmen, in western Föglö (Figures 4 and 5). According to the officers on watch, two thuds were felt and the Överö harbour lights laid to starboard of the vessel's bow.

Figure 5. ms FINNFELLOW aground on the shore of Bockholmen.

1.3 Rescue activity

1.3.1 Initiation of the rescue operation

Activity on board the FINNFELLOW. At 02:35, immediately after the grounding, the officer of the watch called the master, and the pilot reported the accident to the archipelago VTS on VHF channel 71. The master, the first mate and the steward entered the bridge. At 02:42 the steward made a general announcement to inform the passengers about the accident. At 02:45 the master reported the accident to the shipping company. Inspection of the vessel to look for damage was begun under the supervision of the first mate.

Archipelago VTS. The VTS reported the incident to Turku Radio and the Coast Guard. In addition, the VTS promptly notified all other ships in the area of the incident and requested that they use VHF channel 71 if they needed to contact the FINNFELLOW. They were also advised that the fairway at the location of the grounding was navigable but that it had to be navigated at slow speed. At 02:40 the VTS telephoned the FINNFELLOW.

MRCC Turku received a message at 02:38 stating that the FINNFELLOW had run aground at Överö ferry harbour. The MRCC classified the situation as an alert but not a distress. They telephoned the ship to enquire about the situation and were informed that the ship had a crew of 23 on board plus 58 passengers. They were also informed that the vessel's status was being assessed.

At 02:41 the MRCC reported the accident to the coast guard vessel TURSAS and dispatched her to the accident site, where it was estimated she would arrive in three hours. The Åland Coast Station was notified at 02:46. Patrol boat PV 220 was alerted by the station and she arrived at the scene at 03:35, according to the FINNFELLOW's log. Breathalyser tests were given to those on the bridge and all proved negative. The PV 220 brought the navigation inspector to the ship at 05:50.

1.3.2 Evacuation of passengers

The steward led the evacuation team that ensured that the passengers did not come to any harm immediately after the grounding. The passengers then assembled in the mess.

The transfer of passengers to the nearby Överö ferry harbour using a boat from the Åland Marine Rescue Association was begun at 10:50 and completed at 12:25. Several trips were needed to transfer all 58 passengers. The two trainees as well as two crew members were also evacuated from the ship. The passengers were transported from the Överö ferry harbour to Turku via Mariehamn. At 13:45 the shipping company's safety officer reported to the MRCC that the passengers had been evacuated.

1.3.3 Damage to the vessel and her rescue

Identification of the damage. Although the FINNFELLOW grounded at a speed of about 14 knots, the impact with the shore was surprisingly soft. The ship's officers described the incident by stating that "the grounding was soft", "she swung upwards a few times" and "two soft thuds and the bow rose up". The vessel's extremely flat stem (below waterline), which rose up on the shore (Figure 5), provides most of the explanation for the "soft" grounding. This type of traditional icebreaker bow profile, which can be seen from the general arrangement in Figure 2, is common in ice-strengthened ships that are the same age as the FINNFELLOW (constructed in1973).

The first mate and chief engineer commenced inspection of the vessel for damage immediately after she grounded. The first mate was asleep when the vessel ran aground but he was woken up by the impact. After visiting the bridge, and informing the master of his intention to go and check for damage, the first mate went to the cargo office where the vessel's ballast gauges are located.

When the vessel grounded, the boatswain had marked the ballast tanks' water levels on the gauges in red. After observing the status of the tanks for about 15 minutes, the following could be seen:

- Tank 2 was empty compared to its earlier ballast reading of 110 tons
- Tank 3 was full (normal status)
- Tank 4 was slowly filling up (80 tonnes/10 minutes).

The engine room watch immediately sounded the engine room tanks and they were found to be intact. There were no leaks in the engine room itself. The propellor axle clutches were released at 02:40 and the main engines stopped at 02:45.

The chief engineer entered the deck office and together with the first mate checked bottom holds nos. 1 and 2 for leaks, but none were detected at that stage. They went to the bow through the car deck and checked the bow-thruster compartment, where the water level was about 1.5 metres. Because the bow had risen following the grounding (Figure 5), the water level could not rise higher than this either in the bow- thruster compartment or in tank no. 4. As the inspection proceeded, all information about damage sustained was immediately relayed up to the bridge.

The first mate and boatswain then sounded all the above-mentioned tanks. When bottom hold no. 1 was re-entered, there was water on the deck. During these inspections, no grinding was heard nor any movement of the vessel perceived. The cargo had not shifted as a result of the grounding.

After the tanks had been sounded manually, the first mate carried out damage stability calculations using the Onboard NAPA stability calculation software. These calculations were repeated when the vessel was refloated.

After receiving reports from the damage control team and PV 220, the master concluded that the there was no danger of the vessel sinking nor any risk to the environment. At 07:40 the MRCC passed over command to the maritime inspector on board.

Salvage of the vessel. Patrol boat PV 220 sounded around the FINNFELLOW and measured her draught. Divers from the TURSAS checked for damage immediately after they arrived on the scene. They did not detect any holes in the ship’s hull but discovered that she had grounded up to frames 125-132.

The first tug arrived on the scene on the same day at 16:25. The salvage agreement was concluded the same evening and the tugs commissioned by the salvage company – the EMIL, the LENNE and the TEKLA, together with the barge MURSU – arrived at the scene on Tuesday at 04:04. On the following evening, 14 trucks were loaded on board the MURSU. The rest of the cargo was moved over to the aft deck of the FINNFELLOW the following night.

The refloating of the FINNFELLOW commenced at 09:48 on 5 April using two tugs and the ship's own engines. The ship floated off at 11.20 and was anchored.

That same evening divers inspected the damage sustained by the vessel. After the inspection the vessel sailed under her own power, first to Naantali where she unloaded her cargo and then on to Turku repair yard.

1.4 Accident investigation

1.4.1 Initiation of the investigation and the appointing of the board

The Accident Investigation Board’s duty officer received notification of the accident from the MRCC Turku immediately after the grounding at 03:00 on 2 April 2000. The duty officer then reported to the Chief Accident Investigator of maritime accidents. The situation was monitored throughout the night and the next day by keeping in contact with the MRCC and the shipping company’s safety officer.

On 3 April 2000 the Accident Investigation Board decided to appoint a board to investigate the accident. Chief Accident Investigator Martti **Heikkilä** of the Accident Investigation Board was appointed chairman of the investigation board. Heikki **Tissari**, MSc (Tech) of Kvaerner Masa Yards, and Per-Olof **Karlsson**, Sea Captain, of Yrkeshögskola Sydväst gave their consent to serve as members of the investigation board. Kari **Larjo**, Sea Captain, acted as a permanent expert for the board.

The investigators visited the vessel on 5 April 2000 while she was still aground. There, the ship's master and the officers on watch were interviewed. The ship's master provided a maritime declaration at the District Court of Turku on 16 May 2000, a copy of which was acquired by the investigation board.

1.4.2 Special studies made during the accident investigation

The accident investigation proceeded rapidly, since the various pieces of navigation equipment on the vessel provided electrically recorded information essential for the investigation. By making assessments based on the recorded data, the technical functioning of the vessel's navigation system and the contribution of the gyrocompass malfunction to the grounding were able to be verified within a few weeks of the grounding,. The investigation into the underlying gyrocompass malfunction, however, took considerably longer. The technical studies pertaining to the accident were conducted in close cooperation with the owners of the FINNFELLOW, FG-Shipping Oy Ab.

Recorded data from the ship. The following electrically recorded data was available on board the ship: the ship's track; the speed and heading angle, which were recorded by the electronic chart program; and the faults and alarms registered by the gyro system.

Preliminary investigation of the equipment on board the ship. The gyro system assembly, its installation and connections, along with its alarm and fault logs, were studied on board the ship after she had been refloated and transferred to Turku for repair. Instrumentointi Oy provided expert advice during the study. A representative from the gyro's manufacturer was also present. After these studies, the gyro and its control unit were transferred to Instrumentointi Oy in Tampere for further examination.

Examination of the autopilot, and the simulation of the grounding. The operation of the autopilot was studied in the simulator belonging to VTT Manufacturing Technology (Technical Research Centre of Finland) in Otaniemi, Espoo. The steering behaviour of the vessel and her grounding were reconstructed to recreate a similar fault situation to that which had led to the accident. The VTT simulator has an identical integrated navigation system to that of the FINNFELLOW. The data gathered on board the ship about her passage played a key role in this study of the autopilot operation and in the reconstruction of the grounding. Based on this data, Simulco Oy reconstructed from the ship's DGPS registration a recording file. This was used to study the behaviour of the integrated navigation system and it gave the possibility of illustrating the displays as they were prior to the grounding. The simulator was also used for testing what kind of corrective manoeuvre would have been possible after the gyro jammed.The ship's master and the officers on watch were called to the simulator on 2 May 2000 to go through the events which had led up to the accident.

Examination of the gyrocompass. The compass heading was recorded by the electronic chart software. This gave the possibility of studying the function of the gryrocompass. The gyrocompass in use was tested together with its control unit at Instrumentointi Oy, Tampere. The tests carried out on the gyro system included heat and vibration tests and a range of electrical interference tests.

In addition, in the autumn of 2000, the manufacturer performed electrical interference testing on a similar compass system in Kiel, Germany. The board of investigators visited the factory in December 2000 to discuss with the manufacturer's experts the possible reasons for the gyro fault, and they also observed the radio frequency interference tests that were performed on the compass system.

1.4.3 Safety Notice to Maritime Administration

The investigation commission notified October 10th 2000 the Finnish Maritime Administration and the importer of the gyro type on the serious gyro system problem with the grounding of ms FINNFELLOW. The checking and updating of the of the gyro program versions were proposed in this notice.

1.4.4 Statements on the investigation report

In accordance with section 24 of the accident Investigation Degree, the report has been sent for comments to the Finnish Maritime Administration's Maritime Safety Department. The investigation report was also sent for possible comments to the master, the officer of the watch and the pilot of ms FINNFELLOW as well as to the shipowner, MRCC Turku, Archipelago VTS, Sothwestern Maritime District, AT-Marine Oy and Polartec Oy as well as to the manufacturer of the gyro Raytheon Marine GmbH and the manufacturer of the integrated navigation system SAM Electronics GmbH.

Comments were received from Maritime Administration's Maritime Safety Department, the officer of the watch, the shipowner and from both of the equipment manufacturers. The investigation commission has agreed with some of the comments and the report text has been revised accordingly. A list of observed faults and maintenance actions on the FINNFELLOW gyro compass system was also received from the OOW. The comments of the manufacturers are appended to the report.

2 ANALYSIS

The FINNFELLOW carried an Advanced Navigation Software (ANS) system. The ANS presents the DGPS data on its screen with the same graphic navigator data as on the radar screens, the ANS recorded information from the satellite navigator and the headings from the gyrocompass. This data was crucial for reconstructing the accident.

The ANS program registered the following data every other second:

- UTC time
- Latitude and longitude to three decimal places. A DGPS provided positioning accuracy to within a few meters.
- Speed over ground (SOG)
- Course over ground (COG)
- Gyro heading (HDG)
- The vessel’s drift, i.e., the difference between heading over ground and course over ground (HDG - COG).

There was not sufficient recorded data to reconstruct the complete accident turn, as some data was lost during the time that the compass heading was jammed. However, Simulco Oy, as part of its brief from the investigation board, was able to reconstitute these missing compass headings.

The operation of the NACOS autopilot was tested two weeks after the accident on an ATLAS NACOS simulator belonging to VTT Manufacturing Technology in Espoo. Representatives from the shipping company as well as local representatives from the manufacturers of the navigation and compass systems were present during the simulation. The simulation proved that if the heading signal got jammed at the end of the Skarpskär turn in a situation similar to that of the accident, the autopilot would steer the vessel onto the north shore of Bockholmen.

The sequence of events leading up to the accident were reconstructed using the VTT simulator based on the data recorded during the vessel's passage and the reconstituted compass headings. The ship's officers studied the reconstruction and agreed that it corresponded to the accident situation. Using the ANS recording and the NACOS simulator a situation coming very close to the accident could be created.

2.1 Navigation and steering equipment on the vessel

2.1.1 The integrated navigation system and the cockpit arrangement

The cockpit arrangement. A long straight equipment console was installed along the front wall of the bridge when the ship was built in 1973 (Figures 7 and 8). The engine telegraph, the echo sounder and the display for the water pressure log are situated along the centreline. The left side of the console houses equipment of no direct importance to the navigation and steering. The centreline also houses the helmsman's post with the gyrocompass repeater, the rudder angle indicator and the alarms for the steering gear.

The ATLAS NACOS 25-2 integrated navigation system was installed on the starboard side of the console in 1997. One radar was installed at the port end of the console. Two radars, with the autopilot display in between them, were installed on the starboard side (Figure 3). The diagram of the NACOS installation is shown in Figure 6.

Description of the integrated navigation system. Two satellite receivers, a wind gauge, a double-axis doppler log and two gyrocompasses were connected to the navigation system. The system was designed to guarantee that a malfunction in one compass would not jeopardise safe navigation.

The shallow water boundary is programmed into the NACOS as a set of broken lines. Fairway markings and radar targets are programmed as symbols. The piloted routes consisting of straight legs, bends, and routines pertaining to the route, are recorded as files. The lines and symbols are used to create an electronic chart which is superimposed over the images on the radar screen to an accuracy of within a few metres by satellite positioning. The chart is aligned to the correct geographical north with the radar bearing scale.

The echoes from the radar settle on the screen relative to the heading line. The heading is given by the gyrocompass and this always contains an error. The radar echoes based on gyro north do not line up with the true north symbol chart on the radar screen. The compass error may amount to ±2.5° (see Section 2.1.2). The gyrocompass is the most inaccurate sensor in the integrated navigation system. Correction of the compass error is an essential requirement for integrated navigation. The error is caused by the operational principle of the north-aligning system of the current navigational gyrocompasses. This principle is similar for all manufacturers and is based on IMO regulations. Anschütz developed the so-called ballistic correction method in 1990, which reduces the error to about 0.6° only. With such compass accuracy the radar targets and the radar charts remain matched.

The reliability of the compass plays an important role since the NACOS differentiates the rate of turn from the compass. When executing a turn, the autopilot adjusts the rate of turn so that the ratio of the rate of turn to the speed of the vessel matches the turning radius of the passage plan. A compass malfunction would have a direct effect on the control of the rudder.

About 400 coefficients or parameters are programmed into the ATLAS NACOS 25-2, which means that each installation is unique. The coefficients are related to the autopilot, automatic speed control and the way that the information is presented on the screens.

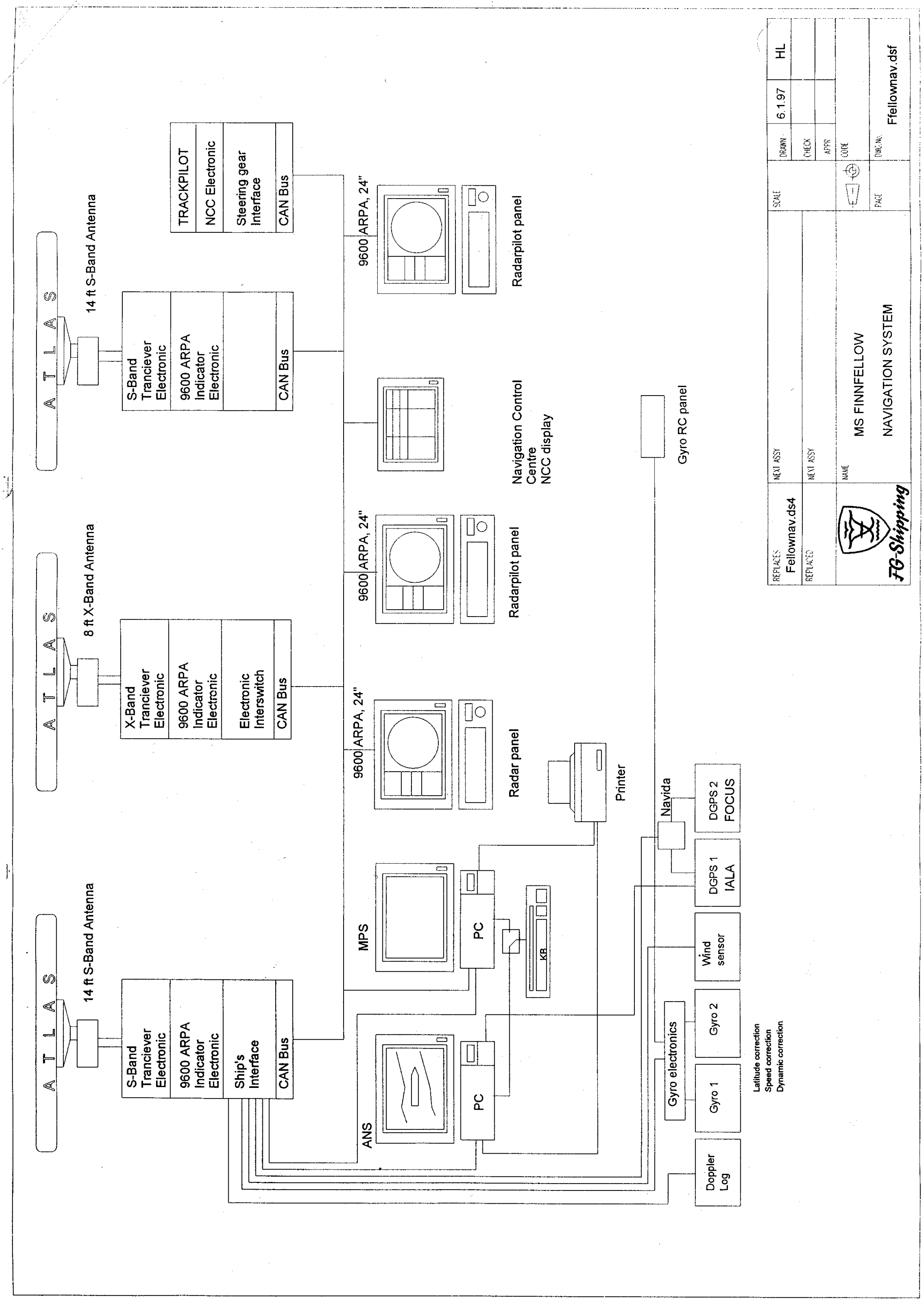
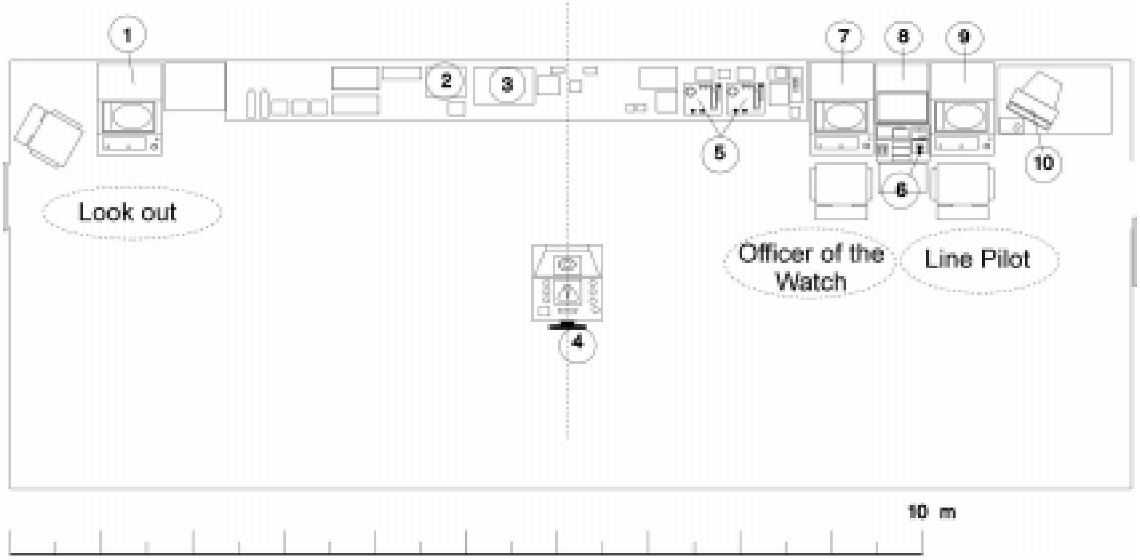


Figure 6. Diagram of NACOS installation on ms FINNFELLOW (including compass connections).



1. ATLAS NACOS 9600 ARPA radar not connected to the autopilot. 2. Talk-Back command relay. 3. SIMRAD echo sounder plotter. 4. Steering post for helmsman. 5. KaMeWa propeller pitch and revolutions control. 6. Follow-Up FU steering lever. 7. ATLAS NACOS 9600 ARPA radar connected to the autopilot. 8. Display of ATLAS autopilot, Navigation Command Console (NCC). 9. ATLAS NACOS 9600 ARPA radar connected to the autopilot. 10. Navigation computer, Advanced Navigation Software (ANS).

Figure 7. Diagram showing equipment on the bridge of ms FINNFELLOW.

Figure 8. Bridge of ms FINNFELLOW.

Autopilot steering modes. The type name of the NACOS autopilot is TRACKPILOT. The steering modes are track mode (automatic track control), course mode (automatic drift correction) and heading mode (conventional autopilot).

TRACK MODE steers the ship automatically according to the track of the passage plan. This steering mode is especially well suited for long, straight, narrow stretches. The pilot or the mate acknowledges the turn 30 seconds before its start and the autopilot initiates the turn according to the passage plan. This mode places great demands on positioning. All alarms related to positioning and the double-axis doppler log disturb the track mode steering.

COURSE MODE is not dependent on the position fix. The vessel can be run on deduced reckoning with course and speed. The autopilot gets the data for the following turn from the route file; this data includes the new heading and the turn radius. On the radar screen the vessel follows the planned graphical turn. The navigator decides when to start the turn. The TAKE OVER command locks the turn trajectory on the radar screen and the autopilot steers along it using the rate of turn as well as longitudinal and lateral speeds and corrects the position of the ship on the trajectory. This steering mode provides the navigator with the option of positioning the turn on the fairway in any way he chooses. Nevertheless, the autopilot maintains its capability to steer correctly in geographical terms according to the turn's pre-set trajectory. The weakest link in course mode steering is the interference with the doppler log side beam, which measures the ship's drift. A doppler alarm indicates that the navigator should disconnect course mode steering.

HEADING MODE represents the lowest level of automation of the autopilot system. It uses only the 'along the keel' speed component of the doppler log. The turning command uses the radius of the turning but the autopilot will not return the position of the vessel onto the arc if there is a deviation. The navigator has to do this manually. The autopilot steers along the pre-planned trajectory of the turn. The autopilot has no link to the geographical plan. The advantage of the HEADING MODE is its technical reliability because any alarms caused by interference from the satellite positioning and the doppler log do not interfere with the steering. This is why the HEADING MODE is quite frequently used during pilotage. The HEADING MODE was in use when the FINNFELLOW grounded. **The reliability of the compass plays a central role in all steering modes.**

Figure 9. HEADING MODE screen of the autopilot (NCC).

The ANS navigation computer displays the position of the vessel on the same symbolic chart as on the radar screen. The ANS was situated to the right of the ATLAS navigation system. The motion predictor, or the coming position of the vessel, was also presented both on the radar and the ANS. The ANS records the track of the ship automatically.

Shipping company instructions regarding the steering system and the training of officers. Prior to implementing the ATLAS NACOS 25-2 system, the officers were trained in its use. Initially the training consisted of two days of theory followed by two days on the simulator. During simulator training the group was divided into three teams: one team operated the simulator, one was trained in the use of the ANS software, and one focused on rule-based work practices or 'procedures' and on monitoring.

The shipping company had issued directions on piloting based on the ISM Code and also on requesting planning of the passage and monitoring of the piloting.

In summary, it can be stated that the cockpit layout and the company's instructions provided a good basis for piloting.

2.1.2 Regulations and experience in the use of the steering equipment

The IMO first issued their **Technical requirements for autopilot** in 1975[1]. This resolution was amended in 1996[2] and contained no technical changes. The amendments concerned ergonomic issues related to the use of the equipment. According to the new resolution, the autopilot had to be capable of executing turns either on the present turning radius or the present rate of turn. Based on this, a turn may be executed according to a pre-determined turning radius by the current autopilots. The same resolution stipulated that the actual compass heading would take over command of the autopilot when it is switched on. The NACOS TRACKPILOT conforms to this resolution. The general requirements for automatic track control were presented for the first time in 1998[3].

Technical requirements which needed to be incorporated into the gyrocompass were first presented in 1979. When in motion, the gyrocompass accuracy should stay within the following limits at latitude 60°:

Rule section	**Nature of error** **Performance standards for Gyro-Compasess** **Res. A.424 (XI), Nov. 1979.**	**Maximum error at 60^{th} lat.**
5.2.2.	The maximum 'settle point error is ±1° × secant latitude	±2,0º
5.2.3.1	The effect of heading change at 20 knots may not exceed ±0,25° × secant latitude after error is corrected	±0,5º
5.2.3.2	Maximum error after sudden speed change at 20 knots	±2,0º
5.2.3.3	Maximum error after heading change of 180º at 20 knots	±3,0º
5.2.3.4	Maximum error may not exceed ±1° × secant latitude when the vessel is in simple harmonic motion due to the waves	±2,0º
5.2.4	Maximum difference between main compass and repeaters	±0,5º

1 Res. A.342 (IX), 1975
2 Res. MSC.64 (67). Dec.1996
3 Res. MSC.74 (69). Annex 2. May 1998

Gyrocompass text books do not take into account the 'settle point' error. A commonly used reference explains 'settle level' as a level above the horizon at northern latitudes where the axis of the gyro settles. 'Settle point error' level with the horizon and is corrected by damping of the compass[4]. According to the resolution, the error may not exceed two degrees (Section 5.2.2).

Ballistic error, caused by the manoeuvring of the vessel, results in an error of a couple of degrees in a turn, even at a low rate of turn. The regulations, however, only allow for an error of 0.5° (Section 5.2.3.1), although they allow greater errors than this for more extreme steering manoeuvres (Sections 5.2.3.2 and 5.2.3.3).

The error caused by waves has no effect on the pilotage (Section 5.2.3.4). The difference between the main compass and the repeater (Section 5.2.4) does not exist in a digital compass.

A practical appraisal of the requirement placed by the resolution under normal conditions and during pilotage is ±2.5°. In integrated navigation, the compass should be accurate to within one degree. The ANSCHÜTZ STD 20 compass, because of its method of ballistic correction, is accurate to less than one degree. This accuracy exceeds the IMO demands by an ample margin.

The same resolution[5] also requires that the gyrocompass be protected from electromagnetic interference as far as is practicable. No limiting values are defined, however.

FINNFELLOW fullfilled the carriage requirements for the navigational equipment given in the Chapter V of the SOLAS Convention. According to these one magnetic and one gyro compass were required[6].

Regulations on the use of the autopilot are presented in the convention Safety of Life at Sea. The possibility of being able to switch over quickly to manual steering should be considered when determining the cockpit layout[7]. In addition, regular testing of both manual and emergency steering is required. These regulations were adhered to in the shipping company's ISM code.

When steering manually the navigation system cannot display the arc to be travelled, but the passage plan can be kept on display at all times. The accuracy with which the autopilot steers along the arc can be monitored using the motion predictor (labelled PREDICTOR in the ATLAS NACOS system). With the predictor, the rudder angle can be set so that the desired position of the vessel on the fairway is achieved. The predictor filters any erroneous rudder angles that are caused by steering the vessel manually, and the effect of the rudder angle on the motion of the vessel can be predicted. Therefore, better accuracy is achieved by steering manually on narrow sections of the fairway than by steering with the autopilot, as the navigator can apply his own experience when steering.

[4] Grant & Klinkert 170, p 399

[5] Res A.424 (XI), Nov. 1979, parag. 7.1: 'All steps should be taken to eliminate as far as practicable the causes of, and suppress, electromagnetic interference between the gyro compass and other equipment on board.'

[6] In the Resolution MSC.64(67) there is a requirement for monitoring the actual heading information by independent heading sources. This applies to control system installations after January 1st 1999. The FINNFELLOW installation had been carried out in 1997.

[7] SOLAS Consolidated Edition 1997, Chapt. V, Reg 19

The steering equipment on the FINNFELLOW provided a good basis for piloting.

2.1.3 Description of the gyrocompass system on ms FINNFELLOW

History of the Anschütz gyro compass. The inventor of the gyrocompass was Dr Herman Anschütz-Kaempfe. He patented the gyrocompass in 1904. The first application had only one gyro. The Anschütz company was established in 1905[8]. Physicist Max Schuler invented the method for the north-aligning gyro in 1911. In 1912 the compass carried three gyros[9]. The main gyro pointed to the north and the auxiliary gyros pointed to headings 330° and 030°.

In 1922 the final technical decisions were made and a construction with two gyros was adopted. When resting, the gyros were at a 90° angle to each other. A sphere containing the gyros floated inside an outer sphere which was physically connected to the compass box. The damping, or weighting system, that turned the compass towards the north was placed inside the gyro sphere. Albert Einstein, who had become friends with Herman Anschütz, designed a coil for the gyro sphere that enabled the position of the gyro sphere to be read and that also turned the outer sphere in the direction of the freely floating gyro sphere[10]. The gyro sphere turned towards north in the chamber and the outer sphere was turned in the same direction using a step motor. Now it was possible to read the compass heading from the attitude of the outer sphere. The Anschütz Standard 1 compass of 1925 was the achievement of three prominent scientists. These technical solutions have remained unaltered up until the present day.

After World War II, full-scale production of the compass only started in 1954[11] commencing with the Anschütz Standard 3 and 4 compasses. The Standard 4 compass became famous for its operational reliability, provided that regular annual maintenance was carried out. The gyro sphere had a lifespan of 3 to 7 years, so the time of its replacement could also be predicted.

The Anschütz Standard 20 (STD 20) was launched in 1994. The size of the gyro sphere was smaller than in previous models but the operational principle remained the same.

When the accuracy requirements for gyrocompasses were tightened, it was Anschütz that introduced the ballistic correction method which made integrated navigation possible. The Nautocourse Plus correction module, which provided ballistic correction, was at first sold separately but it was then later included as standard on the 'Standard 20' compass.

Technical description of the Anschütz Standard gyrocompass. The compass system on the FINNFELLOW consisted of two type-Standard 20 gyrocompasses, a control unit, three repeaters and a rate-of-turn indicator.

The following gives a brief description of the operational principle of the Standard 20 gyrocompass.

[8] Lohmeier and Schell, 1992, p.103
[9] Lohmeier and Schell, 1992, p.23
[10] Lohmeier and Schell, 1992, pp.178, 205
[11] Raytheon Marine GmbH, Compass Digest and interview of Bernhardt Schell in December, 2000.

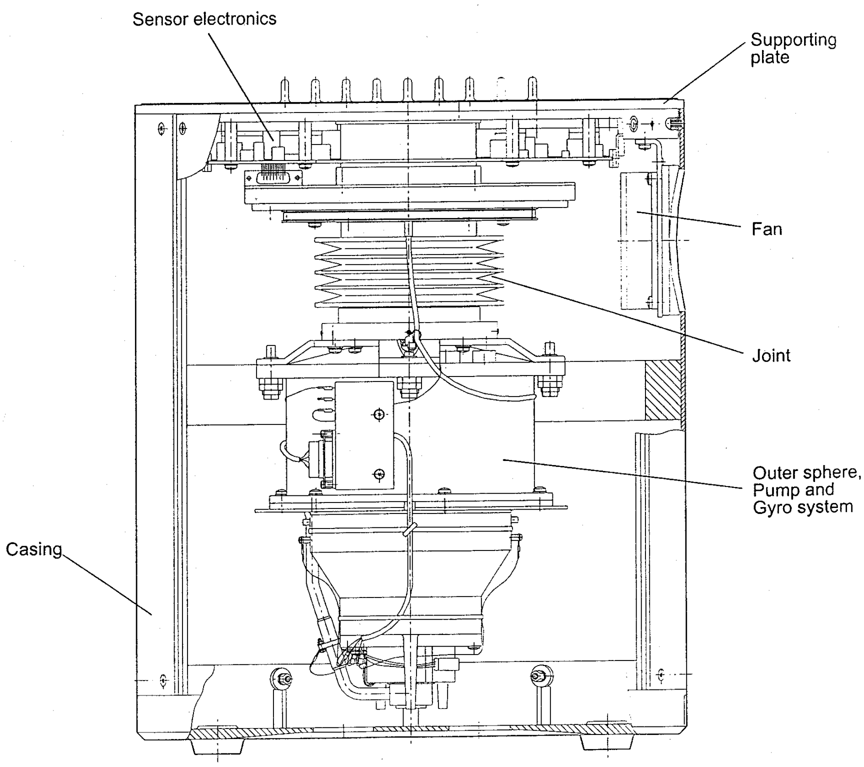


Figure 10. Parts of the gyrocompass.

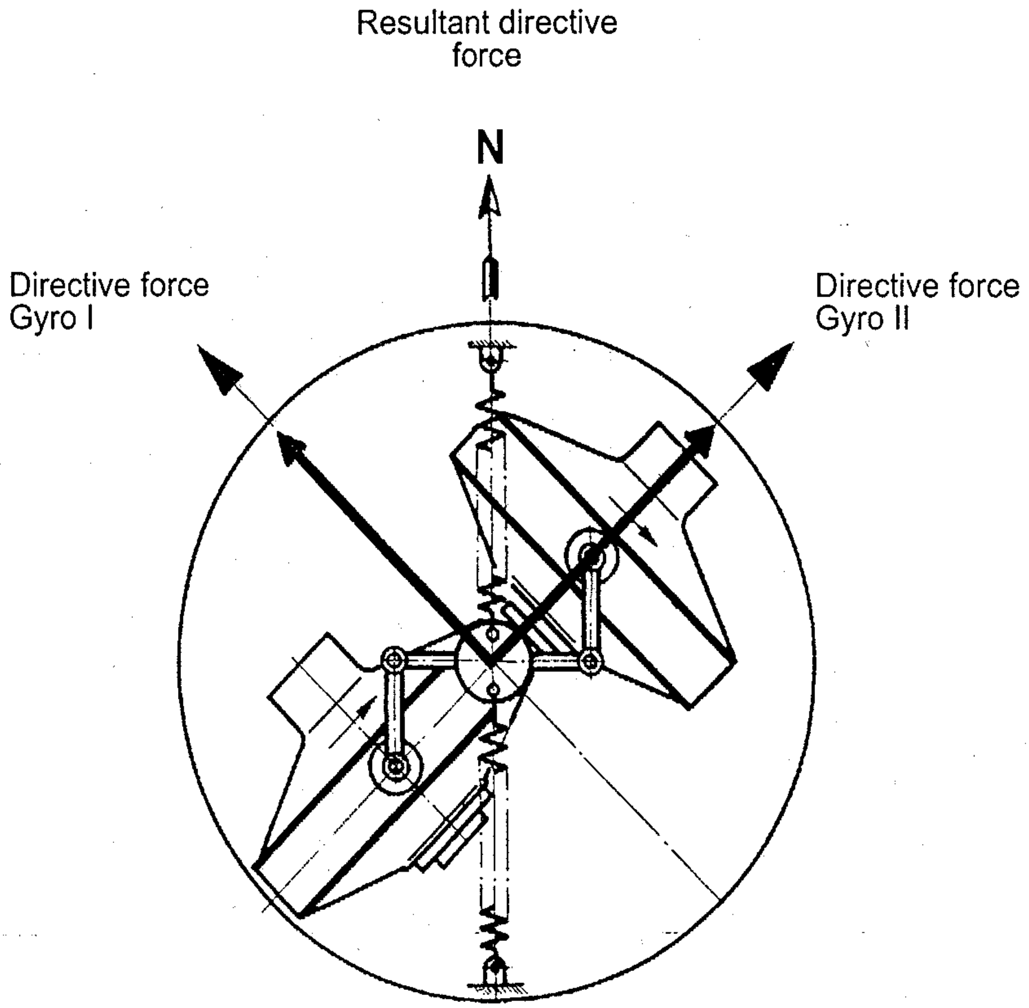


Figure 11. Principle of the gyro sphere.

The parts of the gyrocompass are shown in Figure 10. The operative gyro sphere floats freely in fluid inside an outer sphere and the two gyros and the gyro sphere form a system which points to the north. The principle of the system is demonstrated in Figure 11.

Two electrically operated gyros are installed inside a gas-tight gyro sphere. The combined effect of the rotation of the earth and of gravity creates a force which aligns the gyro sphere in a north-south direction. When the gyro sphere is switched on, the gyro rotors begin to rotate and the gyro sphere oscillates about a north-south axis until it gradually aligns itself in a north-south direction (precessional motion). It takes about three hours after switch-on for the alignment of the gyro sphere to stabilise.

The gyrocompass electronics control a step motor which drives the outer sphere so that it aligns itself with the gyro sphere, if the heading follow-up of the compass is switched on. The ship's heading is indicated by the direction of the outer sphere. The central unit processes the measurement data and transmits the heading information to the equipment in the ship's navigation system. The outer sphere is encased and the user cannot see in which direction it is pointing.

The installation of the gyros in the gyro sphere is such that the rolling or pitching (longitudinal rolling) of the ship does not cause a directional error.

All electrical connections between the casing and the outer sphere of the gyrocompass are made via slip rings.

The gyro sphere always seeks to maintain itself in an upright position in the fluid, with the gyro axles in a horizontal position. The gyro sphere is immersed entirely in the fluid and electricity is fed to the gyros from the outer sphere through the fluid. The pump in the outer sphere keeps the gyro fluid surrounding the gyro sphere flowing constantly. The fluid is pumped against the lower hemisphere of the gyro sphere and the return flow is picked up from the top cap of the outer sphere. The level at which the gyro sphere is positioned inside the outer sphere is affected not only by the density of the fluid but also by its flow from bottom to top between the gyro sphere and the outer sphere. The density of the gyro fluid and the buoyancy of the gyro sphere depend on the temperature of the gyro fluid.

A heat control system aims at maintaining the fluid temperature between 48°C and 50°C. The set value for the temperature is 50°C. The temperature sensor is located on the outer sphere and the signal from it is wired through slip rings to an electronics card in the gyrocompass casing (sensor electronic PCB). If the temperature of the fluid drops below 50°C, the fluid is heated in pulses; if its temperature exceeds 51°C, the gyrocompass fan activates and cools the outer sphere. If the fluid temperature drops below 45°C, constant heating of the fluid (HEATING) takes place and the gyrocompass heading follow-up is disconnected. When the temperature of the fluid falls, the buoyancy of the gyro sphere increases and the sphere may then come into contact with the outer sphere. If this happens, errors may result in the heading information and the sphere may even be damaged. This is why the heading follow-up is disconnected when the temperature drops below 45°C.

Type approval for the Anschütz STD 20 gyrocompass. The FINNFELLOW had two STANDARD 20-type gyro compasses installed on board. The type identification of both was 110-222 and the software version P002E02.01. The software version of the STANDARD 20 compass with type approval is different from that in the gyrocompass on the FINNFELLOW.

In Germany, Bundesamt für Seeschiftfart und Hydrographie (BSH) is the official body that issues type approvals for maritime instruments. The documentation received by the investigators from the equipment manufacturer included BSH type approval documents for the STANDARD 20 gyro compass, type 110-222, software version 110-222.P002E01.xx.

BSH has type-tested and approved the STANDARD 20 gyro compass in accordance with the following regulations and standards (valid 1.1.1999):

Regulations	testing standards
IMO-Resolution A.821 (19)	EN 8728
IMO-Resolution A.424 (XI)	EN 60945
	EN 61162-1

The BSH type approval tests covered gyro compass (type 110-222), the type number of the gyro motherboard was 110-222.101 and of the gyro sphere 111-006. The type numbers of the equipment correspond to the equipment on board the FINNFELLOW.

The BSH type approval certificate numbered 6297/002/99-S4211 is dated 14 July 1999.

BSH performed the type approval testing on the STANDARD 20 gyrocompass between 20 January 1994 and 3 February 1995. The gyrocompass passed the tests according to the following standards and regulations:

- ISO 8728 (August 1987)
- IEC 945 (1988)/ EN 60945 (1993)
- IMO-Resolution A.424(XI)
- IMO-Resolution A.694(17)

The equipment that was tested passed all the tests performed on it. These tests included electromagnetic interference tests, electrical interference tests, and environmental tests. The test report states that electromagnetic interferences were eliminated.

In the electromagnetic interference tests, the intensity of the electromagnetic field used was 10 V/m in the frequency range 400 kHz–300 MHz and 30 V/m in the frequency range 1.5 MHz–30 MHz. The maximum test frequency used, therefore, was 300 MHz.

The type approval documents stipulate that all changes made to the equipment or its documentation must be approved by BSH. According to the information from the manufacturer, this rule does not apply to minor software changes.

Installation instructions for the Anschütz STD 20 gyrocompass and its installation on board the FINNFELLOW. Raytheon has instructions and drawings for the installation and connection of the equipment which makes up the compass system, and also for the earthing of the equipment and its cabling. In the case of the FINNFELLOW installation, there was some deviation from the cable types stipulated in the drawings. The cables connecting the compass system's central unit to the repeaters situated in the steering gear room and on both wings of the bridge consisted almost entirely of old, unshielded cables. The wiring and connection drawing is shown in appendix 3. Even the corrected drawing did not contain a reference to the unshielded cables.

It is Raytheon's policy not to make drawings showing the wiring or the connections from the compass system to other manufacturers' equipment in the navigation system if they do not have overall responsibility for the entire navigation system on the ship. The overall responsibility for the navigation system on the FINNFELLOW was borne by Polartec, the authorised representative of the manufacturer of the system, STN Atlas, in Finland. Polartec carried out the installations and connections on board the FINNFELLOW. The wiring and connection drawings which related to the navigation system on the FINNFELLOW were not forwarded to the gyrocompass manufacturer (Raytheon) as the company had not been responsible for the installation of the vessel's navigation system.

The STANDARD 20 compass system can transmit the heading in both serial form data and STEP signals. The manufacturer of the compass system has not issued instructions about which form should be used for relaying heading information to the autopilot. Heading information was relayed to the NACOS system on the FINNFELLOW using STEP signals. The STEP signal got stuck at the reading which existed prior to the malfunction of the gyrocompass (HEATING status) before the vessel grounded. This jamming of the STEP signal in the HEATING status was caused by the software version of the gyrocompass on board the FINNFELLOW. The serial data output went into a fault status during the HEATING and this resulted in the disappearance of heading information to the repeaters.

On the FINNFELLOW, the STEP signal containing heading information was relayed to the radars, the ANS recording system and the NACOS autopilot. The corrected wiring and connection drawing of the FINNFELLOW's navigation system is shown in Appendix 3. The documentation for the gyro system held on board the vessel did not correspond to the actual gyro system's installation.

Figure 12. The Finnfellow's compass installation photographed during testing on the dock after the grounding. The coiled signal cable is visible behind gyrocompass number 1 on the left.

Connection of the compasses to the NACOS on board the FINNFELLOW. Heading information was relayed to the NACOS using STEP signals. During the installation neither the shipping company nor Polartec, which was in charge of the instrument installation, expected any problems to arise from the use of the STEP signals. The documentation received from the compass manufacturer did not give an adequate explanation of what would happen to the STEP signals in a fault situation. The compass system manufacturer did not classify the HEATING status of the gyro unit as a fault situation, even though the gyro's heading follow-up jammed when the gyro was in the HEATING status.

The operation of the STEP signals depends on the software version of the gyro unit[12]. During the tests performed with the software version of the FINNFELLOW, the STEP signal output jammed to the value which existed before the HEATING status was activated. On the FINNMAID, which is a sister ship of the FINNFELLOW, the STEP signal output goes into fault status if the HEATING status is activated, which results in the navigation system giving an alarm to warn that the heading information is missing.

Software versions of the compass system on the FINNFELLOW. The software versions in use for the gyro unit and the control unit differ considerably from each other with regard to their operation. Depending on the software version, the alarms, alarm filtering, protection of the gyro unit, alarm delays, alarm limits etc. may vary between different software versions. It appears that neither the ship's crew nor even the personnel who maintained the compass system were wholly aware of how the software version installed on board worked. The documentation on board the ship was deficient, especially concerning program updates.

The documentation referring to the compass system on board the FINNFELLOW did not give a firm explanation as to how the STEP course information linked from the compass system to the NACOS would behave if the gyro unit giving the heading information went into the HEATING status. The documentation on board the FINNFELLOW did not explain clearly how the STEP signals operate when the compass is in its HEATING status.

The FINNFELLOW had two gyro compasses on board (configuration G-G). The magnetic compass installed on board was not connected to the NACOS.

The software versions of the compass system on the FINNFELLOW were:

- gyro number 1: type number 110-222, software version P002E02.01 (P002E02.03 on the FINNMAID)
- gyro number 2: type number 110-222, software version P002E02.01
- control unit: type number G401-U0100002, software version 01-001.P01E00.07

The FINNFELLOW's sister ship, the FINNMAID, had one gyro compass and one magnetic compass (configuration G-M).

The FINNMAID carried a similar gyrocompass to that on board the FINNFELLOW, but the software version was different. The gyrocompass on the FINNMAID was operated with software version P002E02.03, but the control unit and its software version were identical to those on board the FINNFELLOW. The heading information from the compass to the NACOS was also relayed using STEP signals on the FINNMAID. When the HEATING status of the gyro giving the heading on the FINNMAID was simulated, the STEP signals went into fault status immediately, heading information disappeared from the NACOS and, after a delay of ten seconds, the NACOS issued an alarm to warn that the heading information was missing. When the gyro giving the heading on the

[12] According to the compass manufacturer "The step signal is generated in the distribution unit (Compact distributor) which is integral part of the control unit. So the software version of the compact distributor is responsible for the functionality of the STEP signals."

FINNMAID was in its HEATING status, the heading readings also disappeared from the repeaters as on the FINNFELLOW.

When comparing the operation of the software versions of the FINNFELLOW and the FINNMAID, the following differences can be detected in addition to the ones mentioned:

1. The gyro follow-up system is disconnected on the FINNFELLOW when the temperature of the gyro fluid drops below 45°C and reconnected when the temperature is again over 45°C.
   On the FINNMAID, the gyro follow-up system is disconnected when the temperature of the gyro fluid drops below 40°C and is reconnected when the temperature is again over 45°C.

2. On the FINNMAID, the filtering of the input from the follow-up system and the temperature sensor of the fluid have been changed compared to the software version on board the FINNFELLOW.

The compass system does not issue any kind of alarm on either ship if the gyro in use enters the HEATING status.

The most crucial difference between the operation of the STEP signals on board these two sister ships is their behaviour during the HEATING status of the gyro. On the FINNFELLOW, the STEP signals jammed when the gyro was in its HEATING status, which resulted in the NACOS not being able to give an alarm. On the FINNMAID, the STEP signals went into fault status when the gyro entered the HEATING status, the heading information disappeared from the NACOS and the system issued an alarm.

The newest software version for the gyro, P002.E02.04, is currently being tested by the manufacturer. In this version, the follow-up system would disconnect if the temperature of the fluid remained below the 40°C limit for at least ten minutes. This new version is likely to require a change in the density of the gyro fluid.

It is natural and right for a company to improve its equipment and software in order to correct obvious errors and to maintain the competitiveness of its product. The investigators have not received a clear explanation from the equipment manufacturer, however, as to why the above changes to the program were made or are being tested. The manufacturer stated that occasional problems with the gyro slip rings was the only reason for the changes.

Back-up with two gyrocompasses. On the FINNFELLOW two gyrocompasses were installed and this gave the opportunity to manually switch from a faulty compass, which was being used to provide the heading, to the other back-up compass. In order for the crew to be able to switch compasses during a fault situation, there has to be an alarm giving a warning that there has been a malfunction. A clear alarm enables prompt and precise action by the crew. There was no alarm given on the FINNFELLOW when the malfunctioning gyro stopped the heading follow-up. The gyros are switched using the control panel shown in Figure 26 (Section 2.2.1).

2.1.4 Installation and operational history of the navigation equipment

The ship's navigation system was renewed in 1997 with the NACOS 25-2. A new Anschütz gyrocompass of type Standard 20 was connected to the system in addition to the magnetic compass. This new gyrocompass (number 1) was installed on board on 9 March 1997. The gyro sphere of gyrocompass 1 was replaced on 19 November 1999 because of problems in its use.

The magnetic compass in the compass system was replaced by a similar Standard 20 gyrocompass on 2 March 1999. No basic components have been replaced in this gyrocompass number 2 since its installation on board the vessel.

Faults and alarms before the accident. Several errors in the heading readings had been observed in the compass system on previous voyages. These faults had been handled according to normal maintenance procedures in connection with maintenance visits.

All the heading errors had been detected on gyrocompass 1. According to the OOW the errors were at maximum over 20 degrees. The maximum reported errors were within the range ±10°. The last maintenance of the gyrocompass before the accident was carried out on 19 November 1999.

The HEATING status activation, which proved fatal for the operation of gyrocompass 1, had occurred several times before the accident. During the HEATING status, the heading follow-up of the gyro stops and the STEP signal output, which relays the heading information to the autopilot and the radars, jammed at the value it had had before the HEATING status. The compass system on the FINNFELLOW did not recognise the HEATING status as dangerous, which is why no sound or light alarm activated on the bridge when the compass jammed. Even the autopilot gave no alarm, because the STEP signal output jammed at its existing value instead of going into fault status. During the HEATING status, the differential alarm between the gyros is locked and this also prevented this alarm from operating during the HEATING status. According to the maritime declaration, the gyro could not be switched using the compass control panel because an alarm activated immediately before the intended switch; this prevented the faulty compass from being changed. This alarm was acknowledged by the master only after the grounding. The compasses can be switched from the compass control panel if no alarm is active. An active alarm must be acknowledged before the operative compass can be changed. The crew had no time to observe what kind of an alarm was activated on the compass control panel immediately prior to the grounding. Even the master was not able to verify which alarm he had acknowledged. The file extracted from the memory of the central unit at the repair dock in Turku contained no record of any alarms. In the file there were two recorded periods of HEATING status on gyrocompass 1, which was the compass in use before the grounding. There may have been two differential alarms, however, because at that time, the ship was turning.

During the HEATING status prior to the grounding, the following list shows the headings which were present on equipment within the navigation system:

- autopilot: heading was jammed at 82.5° (value before the HEATING status),
- repeaters: loss of heading information (only three lines on each display),
- radars: heading information was jammed at 82.5° and the radar image began to get distorted,
- compass system control panel: HEATING message appeared in place of the heading information,
- rate-of-turn indicator: reading was at zero although the ship was turning.

The heading information is distributed to the the repeaters and to the compass control panel as serial data; this is disconnected in the HEATING status. The crew did not detect the loss of the heading information because there was no alarm.

The following are the dates on which the HEATING status activity for gyrocompass 1 were logged into the memory of the compass control unit (Message Log STD 20):

- 25 March 2000: HEATING active 4 seconds.
- 30 March 2000: HEATING active 10 seconds.
- 1 April 2000: HEATING active 1 minute 7 seconds + another period of 44 seconds.

The two last periods of HEATING status are significant with regard to the accident. The precise times (UTC) of these are:

- HEATING on 1 April 2000 began at 23:29:39 and ended at 23:30:46. Duration 1 minute 7 seconds.
- HEATING on 1 April 2000 began at 23:31:30 and ended at 23:32:14. Duration 44 seconds.

The interval between these two periods of HEATING was 44 seconds.

The grounding was logged on 1 April 2000 at 23:32:10 (ANS). The times logged in different pieces of navigation equipment differed from each other (eg. ANS/compass system).

Three alarms indicating the same fault, E4 (see Appendix 4), were logged into the memory of gyrocompass 1. Since there is no time stamp on these alarms, it is not possible to determine their timing with regard to the accident.

Maintenance and inspections. The navigation equipment on the FINNFELLOW was maintained during regular annual service visits and also on maintenance visits as a result of faults or problems reported by the crew. Polartec Oy carried out the following services and installation modifications. The list focuses on the maintenance, repairs and installation modifications carried out on the gyrocompass. The following faults and actions were logged:

1. 9 March 1997. Gyrocompass 1 installed and connected. Operational tests performed.
2. 18 September 1998. Maintenance on gyrocompass 1. The gyro fluid changed.

3. 2 March 1999. Gyrocompass 2 installed. Magnetic compass disconnected from integrated navigation system.
4. 6 November 1999. The alarm "no telegram" remained on the compass system's control panel. This alarm could be acknowledged from the compass system control unit . A similar situation had occurred on 11 August 1998.
5. 14 November 1999. Maintenance on gyrocompass 1 because of 10° errors in the compass heading readings. Gyro fluid changed as part of maintenance.
6. 19 November 1999. Maintenance on gyrocompass 1 because of errors of ±5° in the compass heading readings. Gyro sphere changed as part of maintenance. Operation normal after change of gyro sphere.
7. 3 March 2000. Annual maintenance on gyrocompass 2.

Raytheon Marine gives three years as the service interval for the Standard 20 gyro compass and 40,000 hours as the MTBF value (Mean Time Between Failures). Considerably more maintenance was needed for gyrocompass 1 than for gyrocompass 2. The actual faults causing the above heading errors in gyrocompass 1 may not have been the faults that were addressed during the maintenance visits.

2.1.5 Tests carried out on the gyrocompass

Checks and tests at Turku repair dock after the grounding. During the inspections the parameter readings from the compasses and the compass system control panel were read and logged. All parameter values were within accepted limits. In addition, the events recorded by the compass system control unit, the message log and alarms, as well as the alarms in the memory of the gyro units were read. Fault code E4 had registered in the memory of gyrocompass number 1 three times. These fault codes do not bear a time stamp so it is not possible to determine their timing. The gyro unit fault codes are shown in Appendix 4. The event and alarm log printed from the control unit also included time stamps, which made it possible to link the timing of the HEATING events to the grounding. Section 2.1.4 discusses in more detail the timing and significance of the events printed out.

In addition, the connections and the cabling of the compass system and the other systems connected to it were checked. These were found to deviate from the drawings on board the ship. The drawings of the compass and navigation systems had not been updated and the latest modifications to the installation and the instruments had not been included in the drawings. However, all parts of the compass and navigation system were wired and connected correctly with regard to the existing equipment and the requirements of the manufacturer[13]. The most significant difference between the drawing on board ship and the actual installation could be found in the method used to relay the heading signal from the control unit of the compass system to the NACOS. According to the drawing, the heading information was relayed using a serial line, but in reality the

[13] The cable types did not entirely comply with the manufacturer's recommendation. See also item **Installation instructions for the Anschütz STD 20 gyrocompass and its installation on board the FINNFELLOW** in 2.1.3.

heading information was relayed to the compass system using STEP signals. The corrected drawing corresponding to the actual installations and connections can be found in Appendix 3.

No loose or disconnected cable joints or connectors were discovered during the inspections on the ship. All electronics cards and plugs were sturdily secured with screws. The investigators noted the coil in the long signal cable between gyrocompass 1 and the control unit that was behind gyrocompass 1 (See Figure 12).

The magnetic compass was disconnected from the NACOS by disabling its settings on the compass system control unit's processor card thereby leaving only the two gyrocompasses operative.

No breaks or other deficiencies were observed in the gyro slip rings. This was verified by rotating the outer spheres of the gyros manually.

The gyrocompasses were placed on top of each other at the same angle in order to simulate the HEATING status (see Figure 13). Gyrocompass 1 was selected as the compass giving the heading.

The HEATING status of gyrocompass 1 was simulated by spraying cold spray on its fluid temperature sensor to cool it. When its temperature dropped, the message 'HEATING' appeared on the compass system control panel and the heading readings on the repeaters disappeared (three lines). No alarm sounded and the heading information remained on the autopilot and radar screens. When both gyros were turned the same amount during the HEATING status, no change could be seen in the heading information on the autopilot screen, which meant that the heading readings had jammed to the value they had before the HEATING status. When the temperature of the gyro fluid again reached again 45°C, the heading readings reappeared on the repeaters and the autopilot display was updated to show the correct heading information. The differential alarm between the gyros was activated every time the gyros were turned more than seven degrees during the HEATING status. The printout taken from the control unit after the grounding contained no differential-alarm activations. The differential alarm does not work at all during the HEATING status. It is possible to switch the gyro giving the heading during the HEATING status because the compass system does not interpret the HEATING status as an alarm. The crew on the bridge could not react promptly to the fault in the compass system because the crucially important sound alarm was missing.

Figure 13. Gyrocompasses on top of each other during testing in Turku.

Testing at Instrumentointi OY, Tampere. The gyrocompass in use at the time of the accident and its control unit were tested at Instrumentointi Oy, Tampere. The following heat and vibration tests and electrical interference tests were performed on the equipment. The gyro's manufacturer supplied a maintenance terminal (see Figure 15) and software for the term of the investigation and these were used for recording and displaying the results of the tests.

1. Visual inspection of the equipment, cabling and connections.

   The compass system from the FINNFELLOW comprising the malfunctioned gyrocompass 1, the control unit and the control panel was inspected in detail by Instrumentointi Oy at the company premises in Tampere. No broken parts, connectors or any other fault that could have caused the malfunction in gyro- compass 1 were found during the inspection.

2. Electrical measurements

   The connectors of the electronic units and the status of the slip rings were measured and found to be in order.

   In addition, the system's fault monitoring and alarm functions were tested by introducing breaks into the wiring of all the operationally critical parts of the system. None of these fault situations led to a HEATING status similar to that which had caused the grounding of the FINNFELLOW.

3. Heat and vibration tests

The aim of the heat and vibration tests was to identify possible dry joints, wiring breaks or other faults on the gyrocompass motherboard. Vibration tests were also performed on the control unit to try and identify possible breaks or weak contacts.

During these tests, the gyro compass was placed on a rolling platform (±3 degrees).

The heat tests were performed in the temperature range -10°C to +55°C. The vibration tests were performed in the frequency and amplitude ranges conforming to ISO8728 and also in the resonant frequency range of the ship's propeller.

No malfunctions occurred in the compass system during these tests.

4. Testing for the effect of external electrical interference

These tests were carried out according to *DNV, Rules for ships, HSLL / MOU Jan. 1999; P74 Ch 5 sec. 5.*

4.1. Testing with conductive radio frequency interference at frequency range 150 kHz–80 MHz (gyrocompass motherboard uncased and outside the gyro unit).

The interference frequency range 7.6 MHz–8.8 MHz had the most effect on lowering the temperature reading of the gyro fluid. The interference had the opposite effect on the actual temperature of the fluid because the temperature regulation system of the gyro started to heat the fluid when the temperature reading dropped below 50°C, although the actual temperature remained well above 50°C. The critical temperature with regard to the gyro was 45°C, below which the HEATING status was activated on the FINNFELLOW (see Figure 15). During the HEATING status, the heading follow-up of the gyro does not function, nor does the differential monitoring to the back-up gyro. In addition, the STEP heading information to the autopilot jammed at the value existing before the activation of the HEATING status in the software version that was used on the FINNFELLOW.

During the tests performed on the equipment, it was found that frequency 7.9 MHz caused the temperature reading for the gyro fluid to drop below 45°C, which resulted in the activation of the HEATING mode and jamming of the heading as in the situation that led to the grounding. There were no alarms, only the HEATING message on the control panel of the compass system.

Errors and fluctuations began to appear on the heading-angle display in frequency range 4 MHz– 9.3 MHz.

When the compass system equipment was cased, the above interference frequencies ceased to have any significant effect on the temperature reading of the gyro fluid or on the heading-angle indicator. The test installation did not have the cabling between the control unit and the bridge or other spaces that the FINNFELLOW had.

In the installation on the ship, it is possible that the interference passed to the compass system through the cabling.

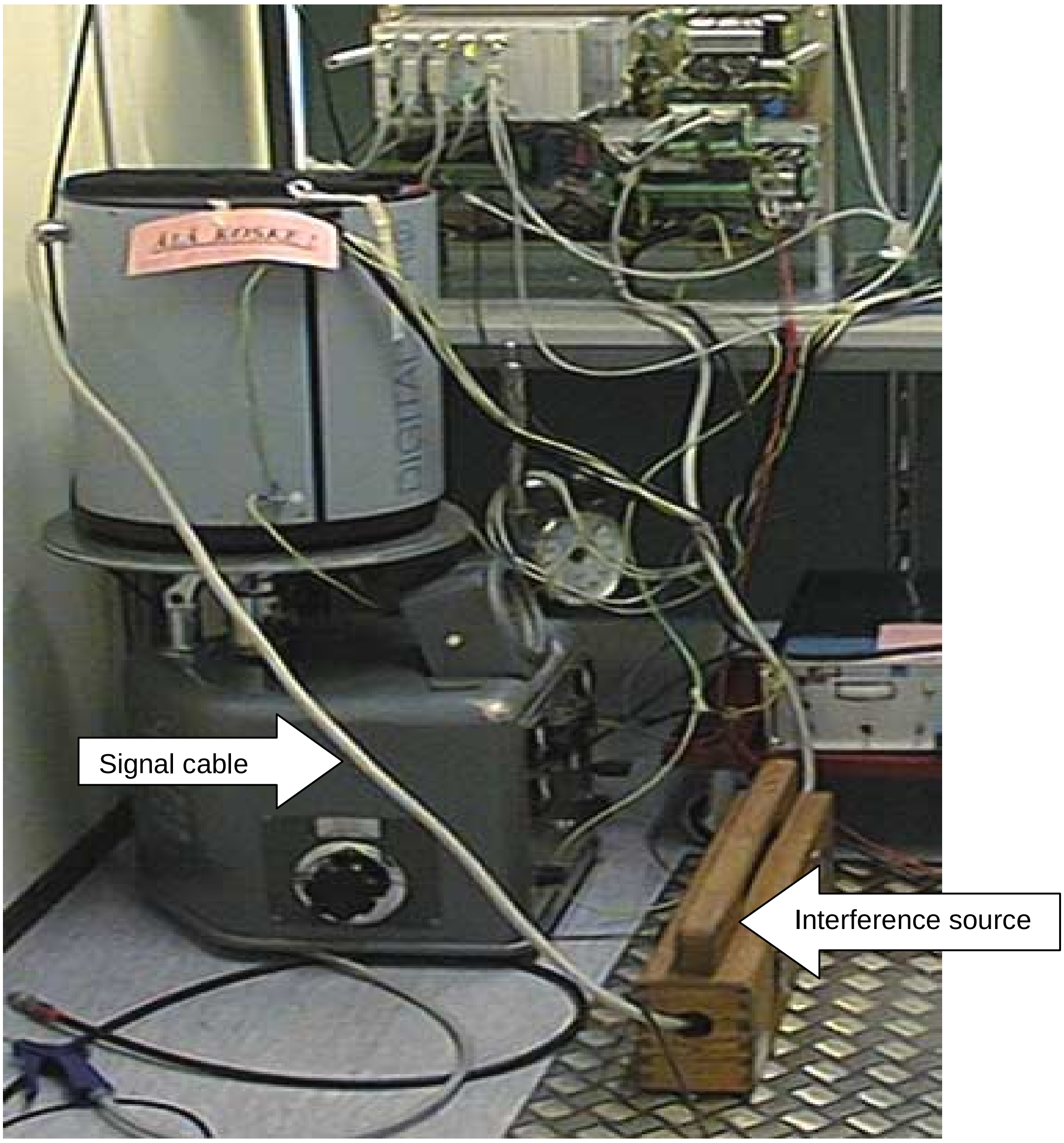


Figure 14. Gyro compass undergoing radio interference testing. The interference was directed at the shielded signal cable between the gyrocompass and the central unit.

4.2. Radiation interference testing (gyrocompass motherboard uncased and outside the gyro unit)

The heading information given by the compass system started to fluctuate at a frequency of 160 MHz (a maritime VHF frequency). At this frequency the heading either developed a constant error of a few degrees or, depending on the strength of the interference, started to fluctuate wildly by as much as ±90 degrees.

The thermal regulation circuit had broken during a 'surge' test when 1 KV had been fed into the feed voltage of the compass system, according to DNV rules. Because of this, there is no way to tell what might have happened to the temperature indication at this frequency.

Other interference frequencies did not cause any significant fault indications during the tests.

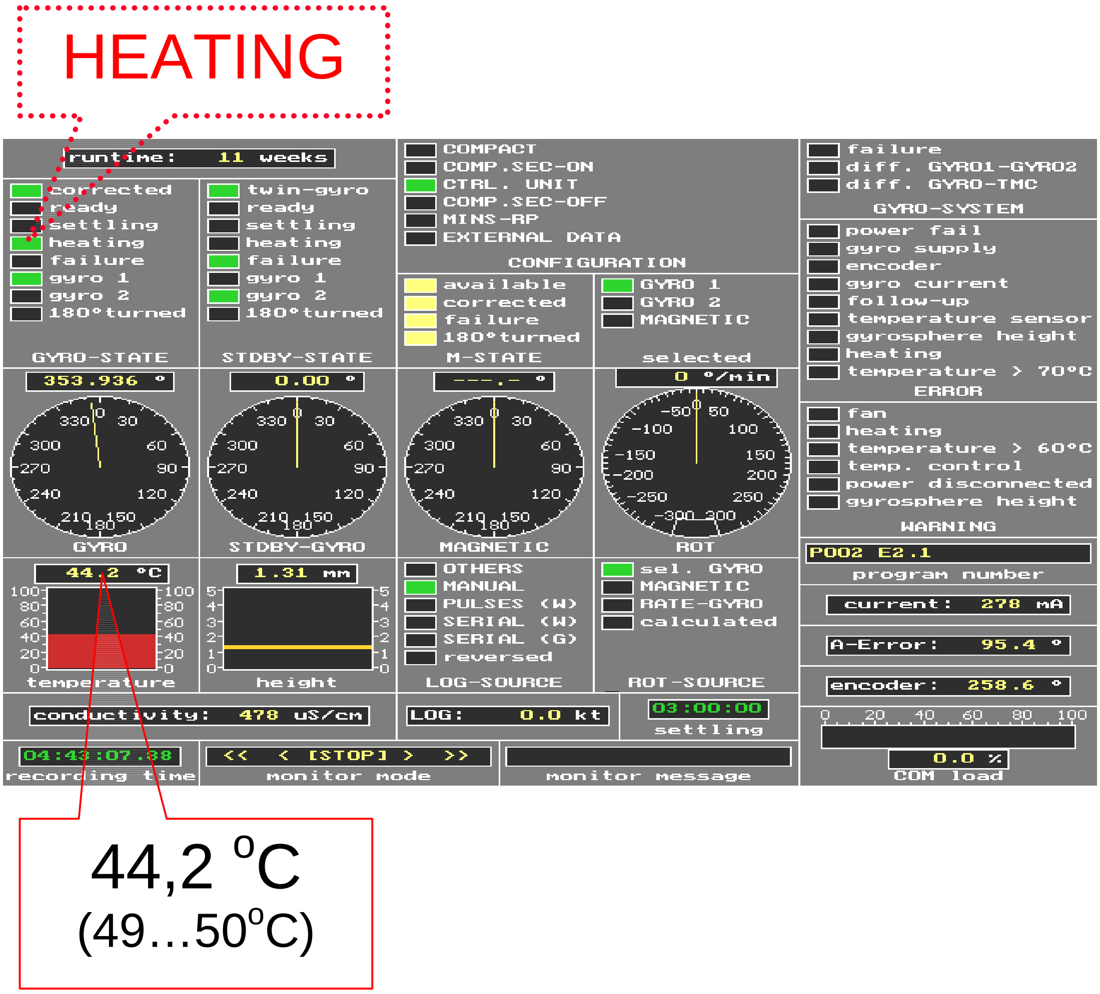


Figure 15. HEATING status caused by external interference as displayed on the Anschütz maintenance terminal screen.

Other radio interference tests. Radio interference tests were also performed on board the passenger ship FENNIA at berth. In these tests the UHF radiotelephone (frequency 457.525 MHz) caused the temperature reading of the gyro fluid to drop below 45°C. The temperature reading of the gyro fluid also dropped at VHF frequencies, several degrees at maximum. These tests caused no error in the heading readings.

When the interference testing equipment was disconnected, the temperature reading of the gyro fluid suddenly dropped by one degree, possibly as a result of radio interference from another ship in the port. The distance between the ships was 40 meters.

Testing at the Raytheon factory in Germany. The manufacturer performed electrical interference tests on a similar compass system in Kiel, Germany in the autumn of 2000. The investigation board visited the factory in December 2000 and tests were performed on the compass system using radio frequency interference while the board was there.

During the radiation interference tests, certain interference frequencies caused errors in the temperature reading of the gyro fluid. UHF and VHF telephones also interfered with the readings if the gyro’s maintenance opening was open.

Summary of the checks and tests performed on the gyrocompass. None of the checks or tests performed after the grounding revealed any kind of structural fault in the malfunctioning gyrocompass 1. The wiring and electrical connections were also in order. The operational parameters of the gyrocompass all stayed within acceptable limits.

As a result of the electromagnetic interference tests, it was discovered that certain frequencies lowered the temperature reading of the gyro fluid. In the laboratory a situation arose where the gyro fluid temperature reading dropped below 45°C, which caused the gyrocompass HEATING status to activate and the heading information to jam. On the FINNFELLOW, the fact that the gyrocompass giving the heading went into its HEATING status caused the vessel's grounding. The tests also revealed that some interference frequencies resulted in a constant error in, or fluctuation of, the heading.

Based on the tests performed on the equipment, it can be concluded that the electromagnetic shielding of the gyrocompass on the FINNFELLOW was not adequate.

2.2 Navigation during the voyage

This analysis is based on the information recorded automatically on board the vessel. The ANS chart display performs this function on board the FINNFELLOW from the ship's interface of the NACOS. The recorded parameters are time (UTC), latitude, longitude, speed over ground (SOG), course over ground (COG), compass heading (bow heading) and drift angle. The heading was jammed and faulty for 66 seconds. Simulco OY used the ANS recording to create a file which could be replayed in the simulator at VTT to reconstruct the vessel's grounding. The simulator replay could be used to analyse the NACOS displays prior to the grounding, as described below. The photographs in Figures 16 to 25 in the next section were taken during the simulator reconstruction.

2.2.1 Skarpskär turn on the navigation displays

At Skarpskär, the FINNFELLOW turned from heading 036° to heading 086°. HEADING MODE had been selected as the steering mode for the autopilot. Figure 16 shows the radar image when the ship is still at heading 036° immediately before initiation of the turn (photographed in simulation replay). The shallow water safety contour is presented as a broken line on the radar chart. The square symbols represent navigational marks. The waypoint (WP) for Skarpskär is not visible on the display as it lies under the heading line, the motion vector measured by the doppler, and the predictor line. (The terms are explained in Figure 17). The tracks were not visible. The vessel was following the planned curved trajectory of the Skarpskär turn (curved headline, CHL). Figure 16 also shows that the pilot made a slightly less sharp turn than projected because it was known from experience that the ship takes a turn slightly to the inside of its intended track.

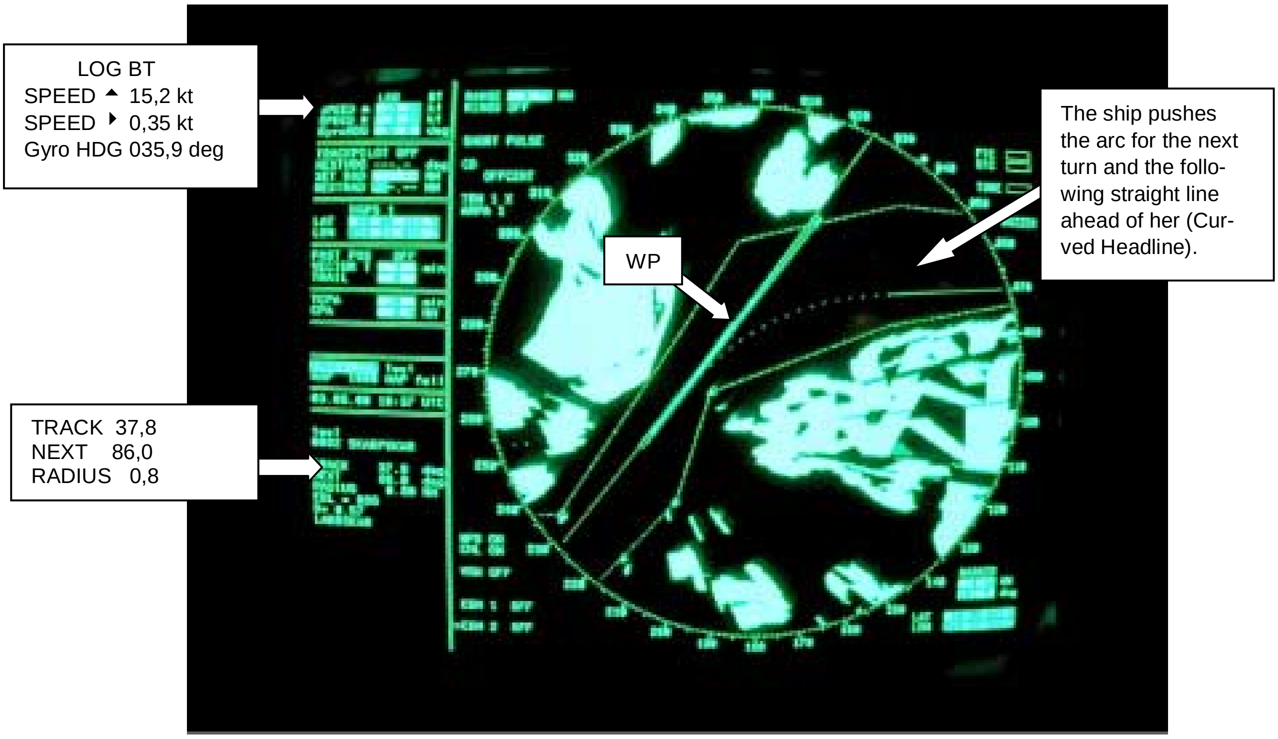


Figure 16. The ship is at heading 036°. Image of the ATLAS radar on the simulator immediately before the start of the turn.

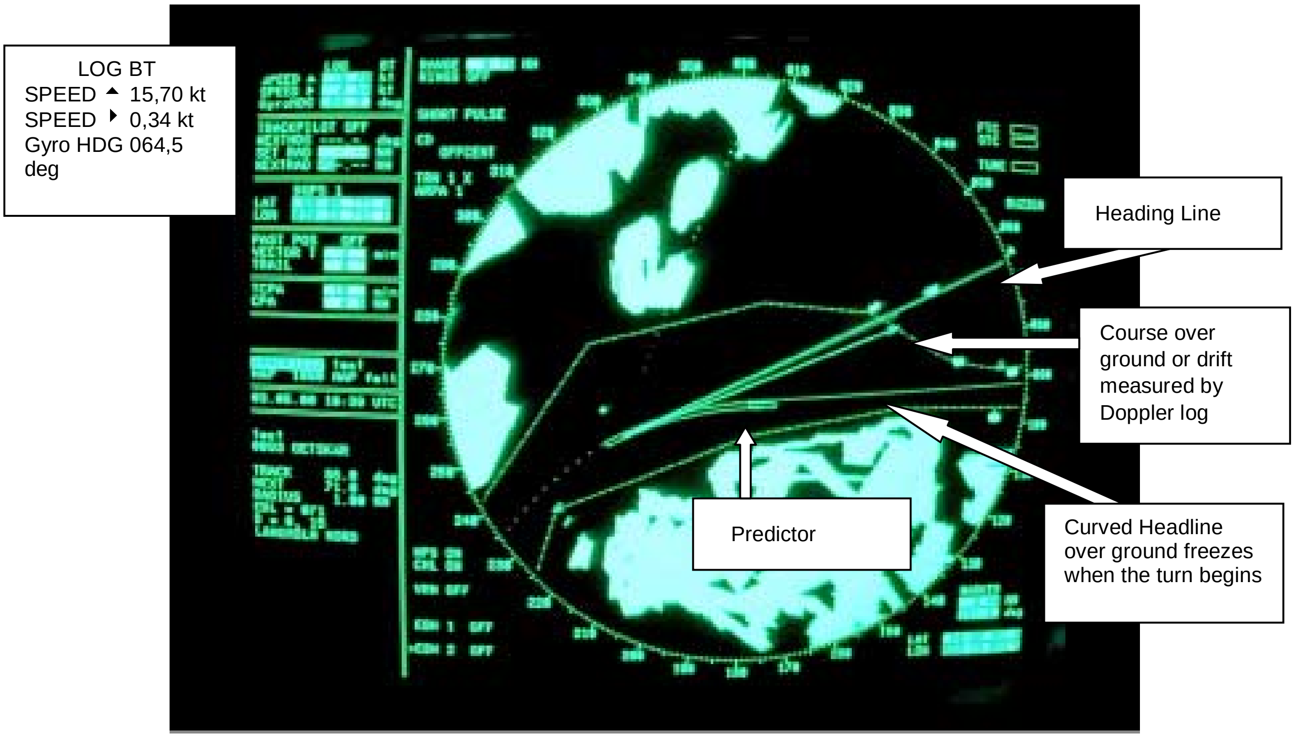


Figure 17. Turn in progress. Image of the ATLAS radar on the simulator during the turn. The image corresponds to clock time 02:30:30 (UTC 23:30:30).

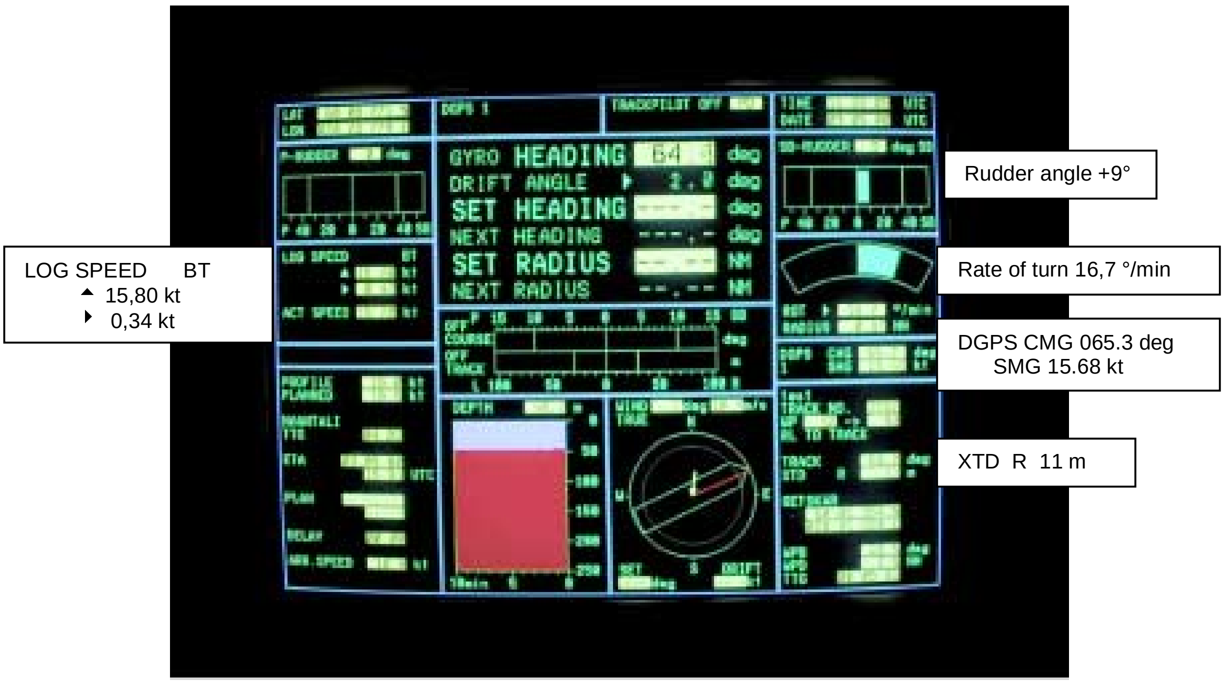


Figure 18. NCC (autopilot) screen. The readings correspond to the situation shown in Figure 17.

The vessel's motion data is shown on the upper left edge of the radar screen. LOG BT refers to the motion over ground measured by the doppler log. TRACK at the lower left of the display refers to the heading that is steered. NEXT and RADIUS refer to the next heading and turning radius of the planned turn. In integrated navigation, Curved Headline replaces the normal variable range marker (VRM) and the electronic bearing line (EBL) in the turn planning. The mate's radar range was set to 1.5 miles and the pilot's 0.75. All the radar image photographs shown here were taken with the radar range set to 0.75.

The Navigation Command Console (NCC) did not automatically read the setting values of the passage plan SET HEADING, NEXT HEADING, SET RADIUS and NEXT RADIUS in connection with the replay in the simulator. On the FINNFELLOW, however, these had been displayed and the autopilot had executed them.

The course over ground measured by the DGPS (CMG) and speed over ground (SMG) are displayed in the centre right of the NCC display (Figure 18). The bottom square on the right shows the lateral distance from the passage plan track (XTD).

The turn is nearing its end in Figure 19. Curved Headline (CHL) has disappeared from the display. The lines connecting the waypoints have been included on the radar image. The radar video has rotated 2° anticlockwise. The IMO allows for an error of this magnitude in its performance standards for radars. The error is not yet detectable.

Figures 19 and 20 correspond to the situation when the gyro has been jammed at 82.5° for 15 seconds. The autopilot display NCC showed false heading information after the gyro jammed:

- Gyro HEADING at the upper edge of the NCC screen had jammed at heading 82.4° (the correct value was 82.5°[14]).
- Rate of turn at the right edge was zero because the NACOS calculates the rate of turn from the heading given by the gyro compass.

The DGPS showed the correct course over ground, 85.5°. The system could not interpret the significance of the various numeric values for the officers on watch.

The autopilot's alarm field was blank. The heading line pointed to a heading where the ship was supposed, and expected, to point. The ship also lay slightly south of the route line, so heading 82.5° was quite appropriate in the situation.

In figures 21 and 22 (30 seconds after the jamming of the compass) the true heading was about 5° starboard of the HEADING reading on the screen. The autopilot tried to turn to starboard to the requested heading 85° from heading 82.5°.

[14] The jammed values for the heading in the simulator reconstruction vary slightly from the actual 82.5º in the photographs taken from the radar and the NCC display.

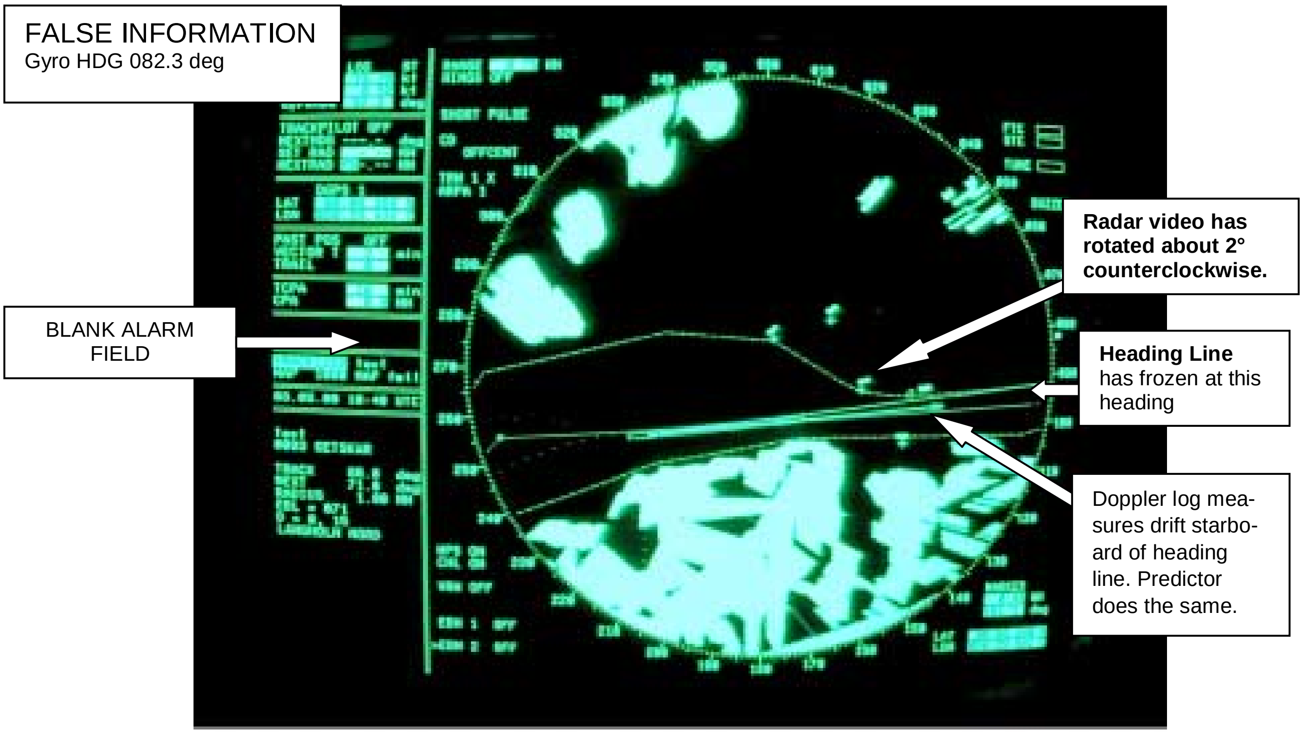


Figure 19. 15 seconds after the jamming of the compass. No report of the compass malfunction. Time of picture corresponds to 02:31:17 (UTC 23:31:17).

Figure 20. 15 seconds after the jamming of the compass. The picture corresponds to the situation in radar image 19.

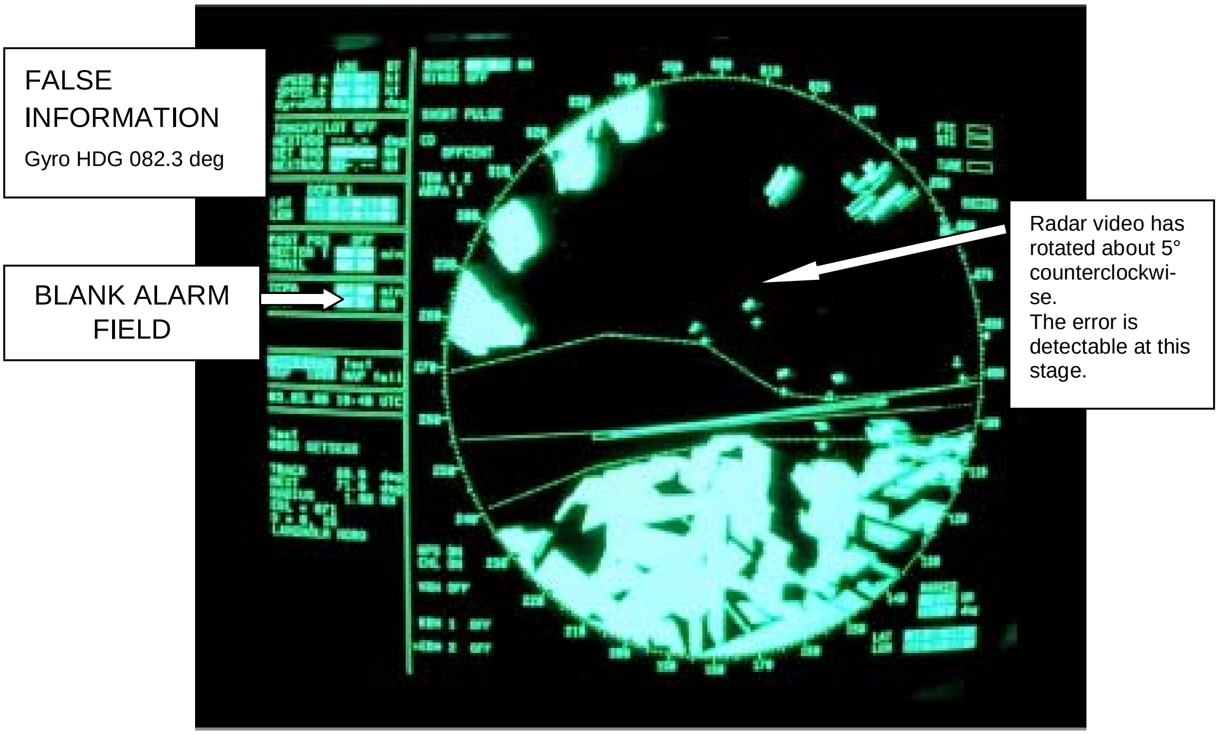


Figure 21. 30 seconds after the jamming of the compass. Time of the picture corresponds to 02:31:32 (UTC 23:31:32). Error can be seen.

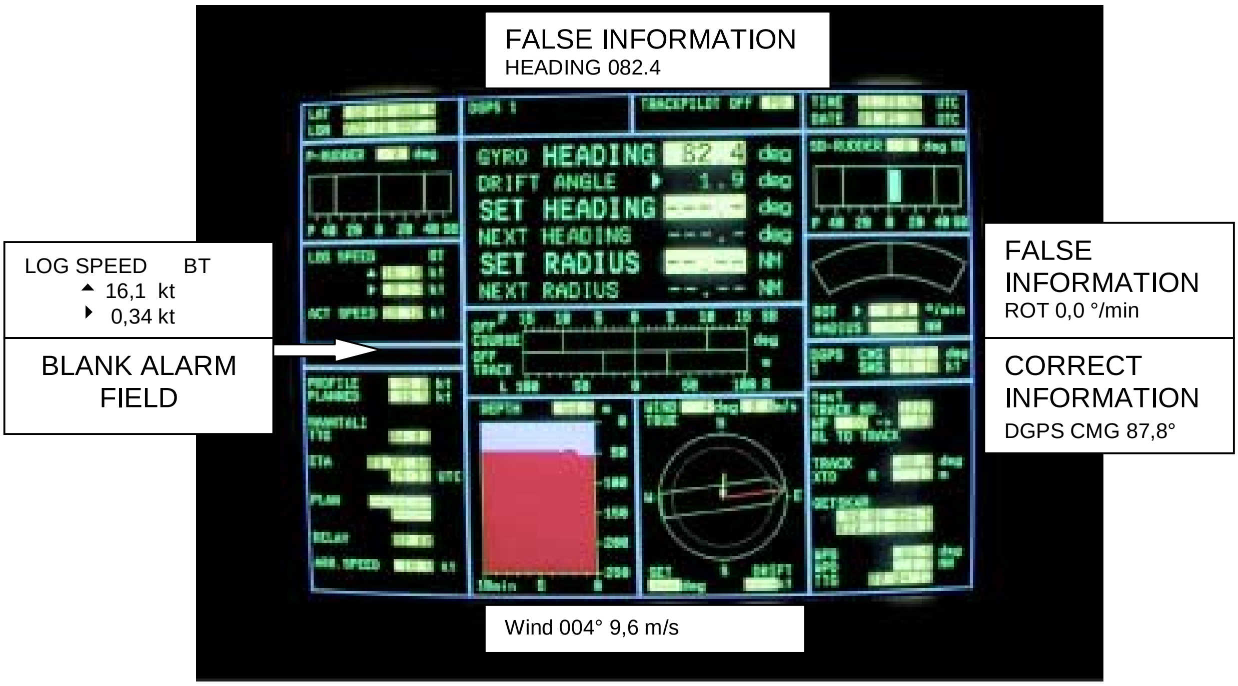


Figure 22. 30 seconds after the jamming of the compass. The picture corresponds to the situation in radar image 21.

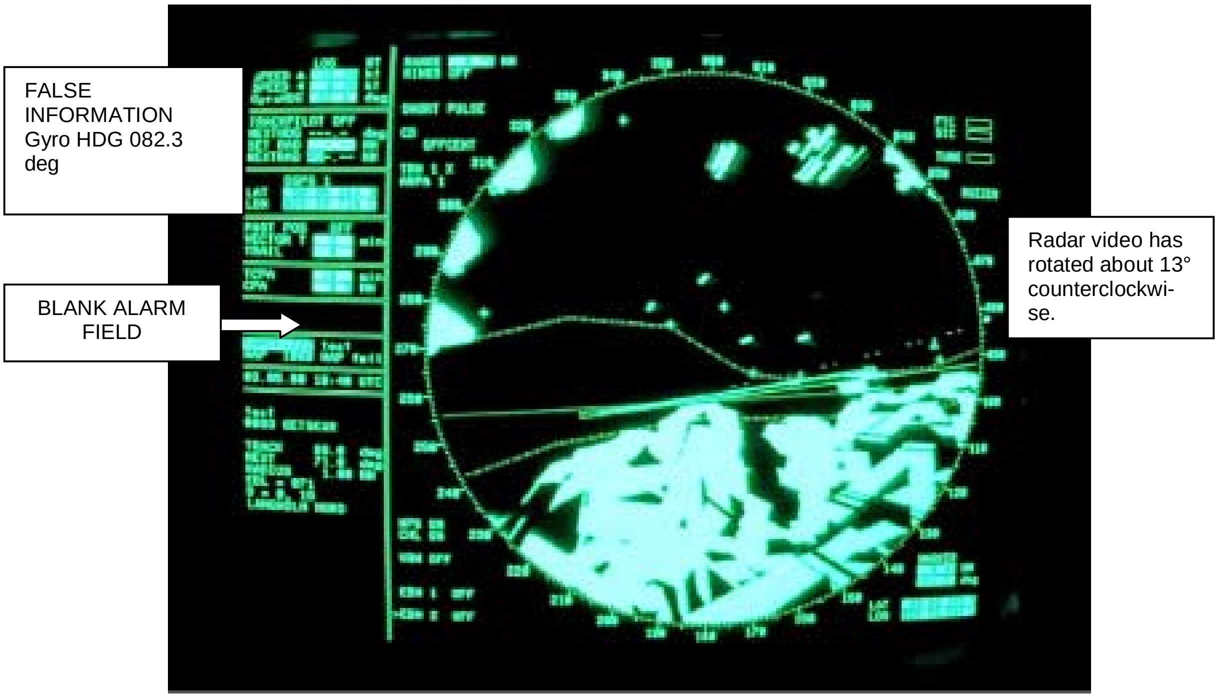


Figure 23. *45 seconds after the jamming of the compass. Time of the picture corresponds to 02:31:47 (UTC 23:31:47). Error can be seen clearly.*

Figure 24. *45 seconds after the jamming of the compass. The picture corresponds to radar image 23.*

In Figure 23 the heading error is easily detectable 45 seconds after the gyro jammed because the shallow water contour clearly overlaps the land echoes. The reason for the error was not visible on the autopilot display in Figure 24.

The monitor for the Advanced Navigation Software (ANS) was situated to the right of the pilot. The computer is used for editing the passage plan, simulating manoeuvres in port, drafting schedules and speed profiles, and recording the passage travelled.

The ANS is always recording during the passage and there is a navigation page on the display. The gyro compass and the DGPS are connected to the ANS program. The passage plan, symbols and shallow water safety contours that are on the ANS display are the same as those on the radar (Figures 25 and 27).

One function of the ANS during a journey is the monitoring of the vessel's schedule. The program can show the times of passing the next six waypoints based on the speeds programmed for the waypoints. The equipment was being used for this purpose at the time of the accident. When every piece of equipment within the integrated navigation system is functioning, the ANS does not provide new navigational information in a dynamic situation. It was natural that the pilot did not monitor the ANS during the turn as he had all the information he needed on the NACOS displays.

The jamming of the compass heading during the turn produces a different outcome on the NACOS and the ANS displays. Both systems calculate the rate of turn from the gyrocompass.

- The NACOS calculates motion over ground for the vessel based on the heading given by the gyrocompass and on the longitudinal and lateral speed from the doppler log. When the compass information is jammed, the drift is plotted based on the old bow heading, which is wrong. The heading line, motion vector and predictor are all wrong (Figure 23).

- The ANS calculates motion over ground for the vessel based only on the DGPS. The predictor, therefore, is not based on the compass heading but on the current tangent of the arc. The ANS cannot, however, display the prediction as an arc because the rate of turn is zero as it is calculated from the gyrocompass heading. The predictor shows the direction of motion for the vessel correctly. (Figure 25).

The ANS display gave a more realistic presentation of the actual situation than the radar screen. Figures 23 and 25 represent the same situation.

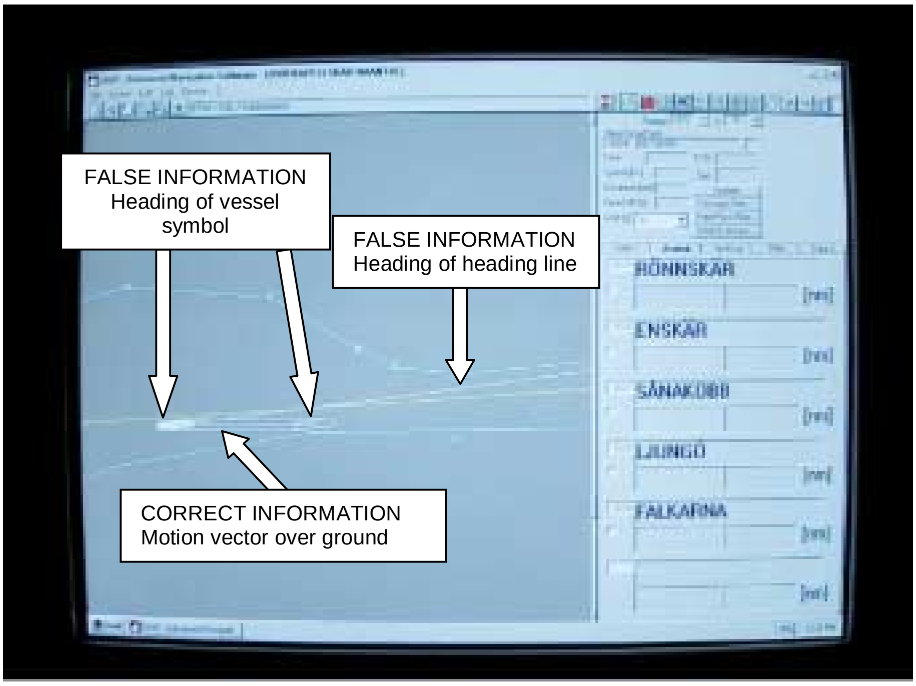


Figure 25. ANS display 45 seconds after the jamming of the compass. The picture corresponds to the time of figures 23 and 24.

Figure 26. Gyro control panel on the FINNFELLOW. In the situation pictured here, the operative gyro is in the HEATING status and the second gyro (in stand-by status) shows the correct readings.

The control panel for the gyrocompasses is located in the FINNFELLOW's steering console under the NCC screen (Figure 3). Figure 26 shows the control panel in a situation where the active gyro is in the HEATING status and the second gyro (in stand-by status) is giving the correct reading. The control panel is only used if there is a gyro alarm. The HEATING status did not produce an alarm.

In summary, it can be stated that the compass fault was not evident either on the radars, the NCC display or the ANS display. There was no alarm on the compass control panel, so there was no reason to glance at it even if the small message HEATING had appeared on the screen with the correct heading of the stand-by gyro in brackets.

2.2.2 Track of the vessel during the grounding

The ANS program recorded the vessel's compass heading and DGPS position every other second. Figure 27 shows the recorded passage of the FINNFELLOW with symbols showing the vessel's track in the Skarpskär turn. The compass reading jammed at 23:31:02 and then started to give the correct heading again at 23:32:08. This break of 66 seconds was fatal. The data recorded by the ANS and the report made on it by Simulco OY are appended to this report.

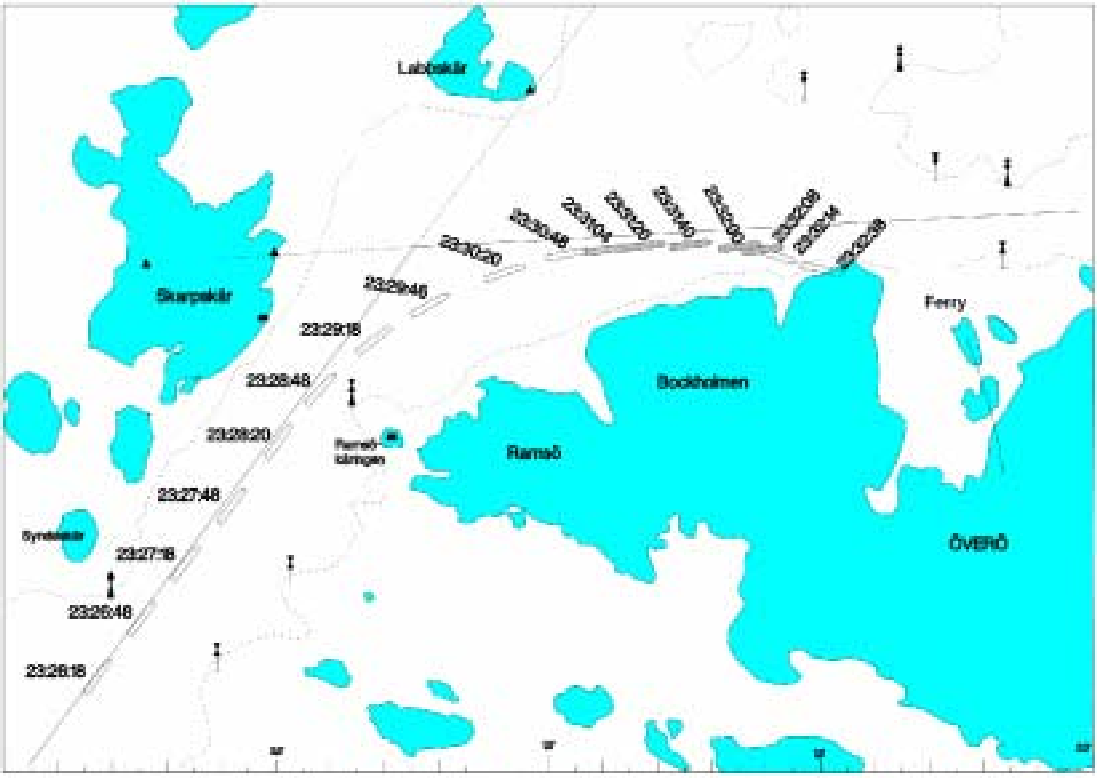


Figure 27. Data recorded by the ANS during the Skarpskär turn. The compass heading was jammed between 23:31:02 and 23:32:08.

The beginning of the Skarpskär turn proceeded according to plan (Section 2.2.1 and Figures 16-18). Even though the turn was started slightly later than normal, the trajectory of the vessel cut slightly in the bend. The autopilot's HEADING MODE tends to cause this and the north wind also contributed.

The autopilot's heading command was 85°. Because the vessel remained slightly south of the line, the pilot prepared to adjust the heading slightly to port. The speed of the vessel slowed down due to turning. The compass jammed at heading 82.5° at 23:31:02. There were no alarms. The autopilot appeared to execute the turn according to plan.

In the ANS recording the vessel's attitude seems unnatural between 23:31:02 and 23:32:08 (shaded symbols in Figure 27 and Figure 28). In this part, the vessel moves to starboard at a considerable drift angle.

The NACOS converts the geographical coordinates of the DGPS antenna into the same coordinates as the Doppler log sensor, because its location acts as the point of origin for the NACOS system (Figure 29). The system also sends the Doppler coordinates to all its auxiliaries. Therefore, the ANS also records the geographical location of the Doppler sensor. The change of coordinates has no effect if the compass operates without faults. When the compass heading jammed, and the vessel was turning, the NACOS transferred the location coordinates from the DGPS antenna to compass heading 82.5° while the heading of the vessel was turning inconspicuously further to starboard, all the way to 110°. The recorded position was therefore outside the true contour of the ship. The ANS recording for this part is shown in Figure 28.

The ANS screen presented the end of the turn as shown in Figure 28 (see also Figure 25). The radar heading line pointed to heading 82.5° and the radar vector (COG) showed a drift to starboard. These readings were misleading.

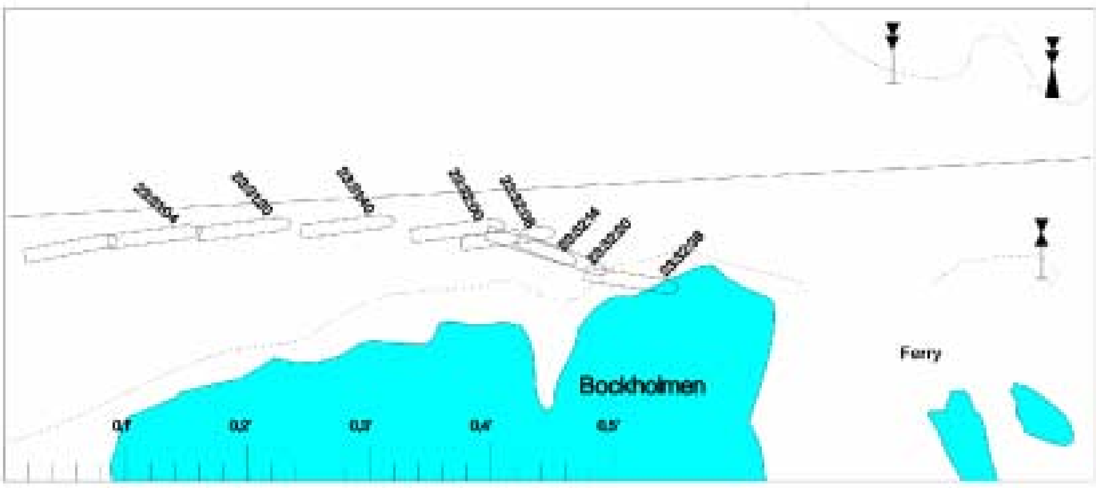


Figure 28. ANS recording became distorted when the compass ceased to operate. The ship symbols between 23:31:02 and 23:32:08 do not show the true heading of the vessel.

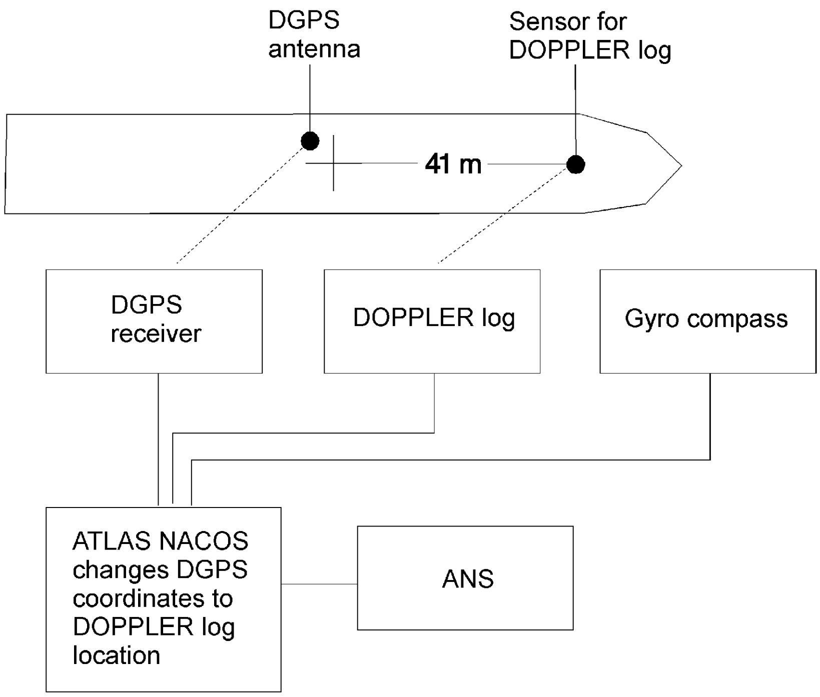


Figure 29. The origin of the NACOS is situated at the Doppler sensor.

The true situation of the vessel was not shown on any display. The actual turn is reconstructed in Figure 30. Simulco Oy determined the true headings for the time interval when the signal output was jammed[15]. Reconstruction of the track was executed so that the vessel symbols were turned to the actual headings with regard to the centre point of the vessel. The shaded symbols in Figure 30 were turned according to the corrected heading definition. Had the compass functioned correctly, this is how the ANS recording would have looked.

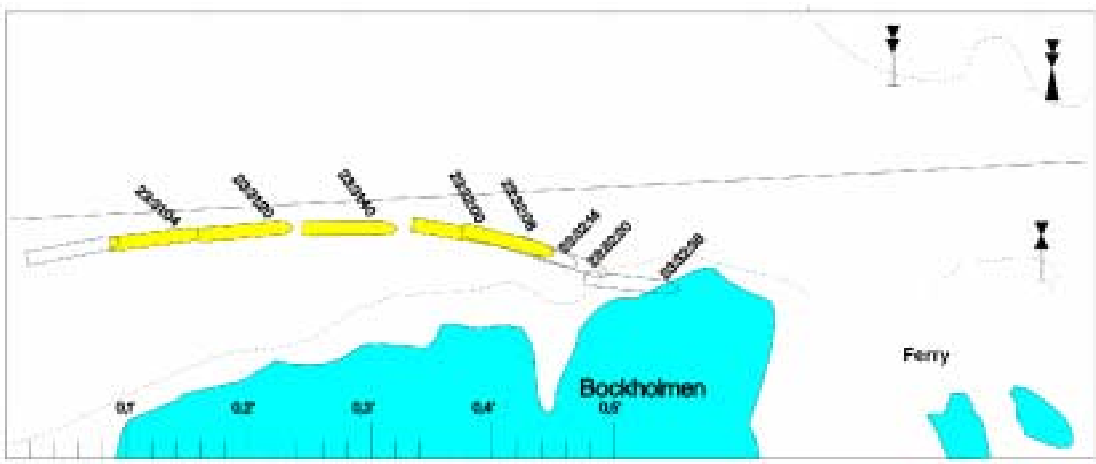


Figure 30. The grounding shown with the reconstructed true compass headings. The shaded vessel symbols show the actual passage where the compass heading was jammed.

[15] Report by Simulco Oy appended

2.2.3 Corrective manoeuvres and the available time margin

Executed corrective manoeuvre. After the compass had jammed 2.5° short of the final heading in the turn, the autopilot attempted to achieve heading 85° according to its command and the heading began to change increasingly to starboard. The rotation of the radar video anticlockwise was the first observable indication of the gyro malfunction. It indicated that something was wrong. Experience has shown that it is difficult to detect a compass malfunction because the compass is connected to all the other equipment and it acts as a base for the entire system. The first reaction is not that the entire navigation system has crashed.

The officer of the watch noticed that the lateral distance of the vessel to the line was about 15 meters and that the bow heading had slid to starboard of the line lights. He was about to mention this to the pilot when he also noticed that the radar chart was not in its correct position and realised that there was a malfunction in the compass. The radar image had become fuzzy. The rudder was 20° to starboard. The pilot turned the rudder manually to full port. It is not possible to define the exact location where this was done but the starboard turn stopped at 23:32:25 and the vessel began to turn to port.

Corrective manoeuvre analysed in the simulator. Avoidance manoeuvres were performed in the simulator to determine how much time there was to react to the fault situation. Figure 31 shows the situation where the rudder was turned hard to port 44 seconds after the compass jammed.

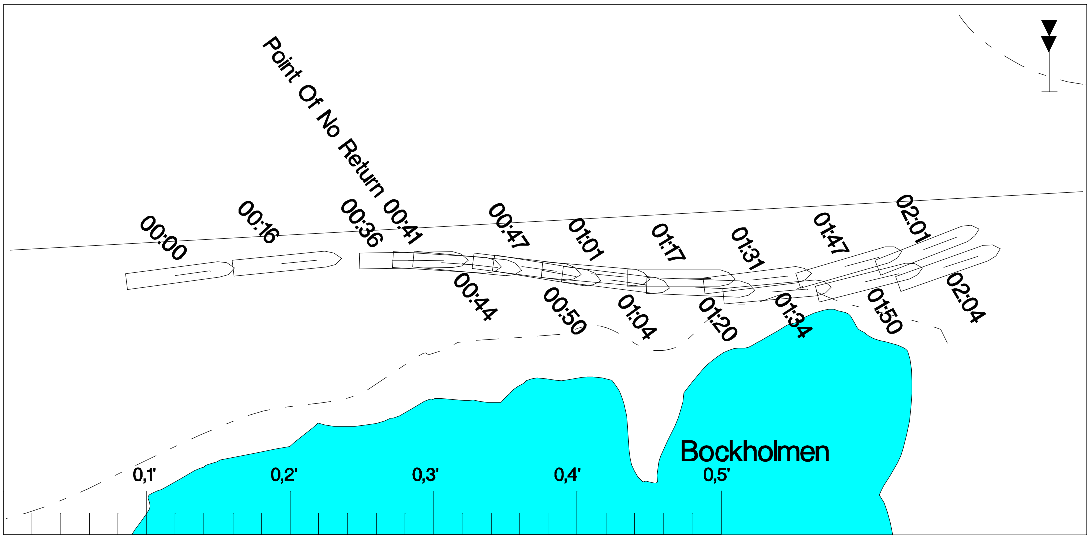


Figure 31. The time of the jamming of the compass has been marked with zero in the picture. The simulated avoidance manoeuvre began at 00:44 but this was slightly too late. The rudder must be turned to port about three seconds earlier. The 'point of no return' is 41 seconds after the jamming of the compass.

It was not possible to program the bank suction effect into the simulator. The stern of the ship would probably have been influenced by a strong bank effect so close to the shore. Thus the simulated turn was reconstructed to begin three seconds earlier at 00:41. The rudder had to be turned to starboard at the latest 41 seconds after the compass jammed. Had there been a HEATING status alarm and had the compass readings been correct, the officers would have had time to act. This theoretical time margin is discussed in the following, first from the point of view of the rules and then from a practical viewpoint.

Available time margin. When determining the available time margin for the officers to act, the compass error allowed by the IMO and the regulations on how quickly the autopilot must be switched off are considered. The resolution of the compass[16] allows a maximum error of ±2.5°, which was achieved about 15 seconds after the compass jammed. The situation as it stood 15 seconds after the compass jammed is shown in Figure 19. The IMO resolution on the autopilot[17] requires that it must be possible to switch off the autopilot in three seconds. In other words, the IMO regulations allow for a delay of 18 seconds. The compass error and the delay in switching to manual control allowed by IMO leave a time margin of 23 seconds to initiate the corrective manoeuvre.

The delay cannot be considered only from the point of view of the rules since there was no alarm. The officers on watch had to deduce the deviation from the route either visually or from the radar. The radar images of Figures 19 and 21 show the situation 15 and 30 seconds after the jamming of the compass with the corresponding compass errors of 2° and 5°. In the opinion of the investigators it can be concluded from the radar image that there is a technical fault in the navigation system when the compass error exceeds about 5°.

The way that the integrated navigation system shows the compass error is confusing because the chart maintains its orientation but the radar targets begin to turn (Figure 23). It is difficult to determine quickly which is correct, the chart or the radar. The fault could also be in the radar antenna. It is difficult to estimate how long it takes to identify the source of the fault. In this accident, the officer of the watch acted quickly but still there was not enough time.

2.2.4 Summary of the operation of the navigation equipment during the accident

The satellite navigation was operating correctly at the time of the accident. This can be verified from the data registered on the vessel. Also the Doppler log was correct.

The integrated navigation system was operating as planned. The autopilot performed the right corrective manoeuvres based on the compass heading, but no information about the jamming of the heading was received by the autopilot.

[16] IMO res. A.821(19) 23 Nov.1995. par.4
[17] IMO res. MSC.64(69) 4 Dec. 2000 par. 4.1.

Within the compass system the Anschütz STD 20 gyro sphere was operating correctly inside the outer follow-up sphere. The heading follow-up of the gyro compass jammed at heading 82.5° at 23:31:04 (UTC). The heading follow-up was restored at 23:32:12 (UTC) when the compass heading suddenly jumped to starboard to heading 100.8°. The jump to the correct heading showed that there was nothing wrong with the gyro sphere, which had been at the correct heading all the time, while the heading follow-up had been switched off according to the in-programmed logic.

2.3 The collapse of the gyrocompass heading protection

There are regulations, technical solutions and fault analyses for ensuring accurate relaying of the compass heading from the compass to other systems. These form protective systems that are expected to stop the chain of events leading to an accident. In the case of the FINNFELLOW, the protective systems failed.

2.3.1 Gyro fault analysis performed by the manufacturer

Raytheon had performed a Failure Mode and Effect Analysis (FMEA) on the Anschütz STD 20 compass[18]. The results of this analysis performed in 1998 are summarised in Appendix 5. The analysis, according to the international FMEA standard,[19] is designed to define the consequences of equipment faults.

The HEATING status that occurred on the FINNFELLOW is only one of ten fault situations that could result in the disconnection of the heading from the compass to the navigation system.

In most of these fault situations the gyro system monitors the gyro parameters: e.g., temperature, fluid level, power supply etc. It is possible that, mechanically, the compass gyro sphere will still operate correctly immediately after passing the maximum or minimum limit because the inertia of the gyro is strong and the change in the parameter is gradual. In such a case, the program disconnects the heading information to the peripheral equipment even though the system has a fault situation that does not affect the direction of the gyro sphere itself. Faults in the control unit, where the system also switches off the heading information to the autopilot, increase the total number of these fault situations.

To summarise the FMEA, it can be stated that no conclusions have been drawn from the analysis of the fault situations. The fault situations have been evaluated only with regard to the compass system itself. The analysis takes no stand on what effect the disappearance of the heading information might have, nor has the effect of this disappearance on the safety of the ship been addressed.

[18] This FMEA was performed for the Raytheon Marine Integrated Bridge System (IBS) including also STANDARD 20 compass.

[19] International Electrotechnical Commission, IEC, Analysis techniques for system reliability - procedure for failure mode and effect analysis (FMEA). Publication 812, 1985.

2.3.2 International regulations

The IMO regulation on gyro compasses recommended in 1979 that the gyrocompass be protected against electromagnetic interference and that an alarm be issued in the case of a serious fault situation[20]. This is a detailed regulation that can be applied in practice.

The ISM Code requires that the shipping company establish a safeguard system in the form of guidelines[21] against all risks. This general requirement is difficult to carry out.

The grounding of the FINNFELLOW showed that equipment safety cannot be achieved with the present regulations, safety analyses and certificates. During type approval, individual equipment is tested for electromagnetic interference under laboratory conditions. In vessel installations these tests are not performed, nor do the annual equipment surveys stipulated by the regulations remedy the situation.

2.3.3 Two compasses and the differential alarm

The SOLAS requires a gyrocompass and a magnetic compass for a ship the size of the FINNFELLOW[22]. The shipping company had ensured equipment safety with the fitting of the second gyrocompass. The reliability of the compass heading was ensured with a function of the control unit that gives an alarm when there is a difference in reading between the compasses[6]. The comparison of the difference operated only when both compasses were functioning normally. There was no alarm as a result of the fault. The only indication was the message 'HEATING' on the control panel, Figure 26 (Section 2.2.1).

The compass system was programmed to consider the HEATING fault status as a normal function with no alarm. The same fault was still considered a disturbance requiring disconnection of the heading follow-up on the peripherals. When the heading follow-up was disconnected, the control unit program prevented the activation of the differential alarm.

The FMEA analysis had not had any effect on the programming of the operation of the differential alarm. The two gyro compasses and the differential alarm did not improve safety. The system operated as if it only had one compass.

2.3.4 Connection of the compass to the autopilot

Raytheon is responsible for the drawings showing the connections from the compass to other equipment only if this other equipment is manufactured by the company itself. If the Anschütz compass is connected, for instance, to the NACOS, then Raytheon does not take responsibility for the connections nor give out instructions for them.

[20] IMO res. A.424 (XI) 15 Nov.1979, par. 7.1 "All steps should be taken to eliminate as far as practicable the causes of, and to suppress, electromagnetic interference between the gyro compass and other equipment on board" and par. 9.3. "An automatic alarm should be provided to indicate a major fault in the compass system"
[21] IMO res. A.788 (19), 23 Nov.1995, Annex par. 2.2.2: to establish safeguards against all identified risks;
[22] SOLAS 1974 (1997), Chapt. V, reg. 12.

Traditionally, the compass has always been connected to other equipment by an analogue STEP signal. This requires that each piece of equipment is separately set on the correct heading. The STANDARD 20 compass STEP signal may behave in two different ways in a fault situation depending on the software version of the gyrocompass. In one version, the heading signal jams and in the other it is not sent (see Section 2.1.3, paragraphs "Connection of the compass to the NACOS on board the FINNFELLOW" and "Software versions of the compass system of the FINNFELLOW").

The STANDARD 20 compass also transmits the heading information digitally in serial form. The protocol is NMEA 183. Its advantage is that the other pieces of equipment automatically get the correct heading. In a fault situation, the heading information is not transmitted.

Only the STEP signal was connected on the FINNFELLOW. Raytheon did not require the use of a serial signal in its installation instructions for the compass.

The disconnection of the compass signal affects the integrated navigation system by immediately putting the radars into their HEAD-UP display. The HEAD-UP display is infrequently used nowadays, so that if the radar suddenly presents a HEAD-UP image it causes confusion that may lead to an accident. If HEAD-UP suddenly appears in fog during a turn, or when steering in a southerly direction on a narrow fairway, an emergency arises. The serial signal is no guarantee of safety in all situations. The navigator must act without delay as follows:

1. Follow-up manual steering must be activated at once.
2. The magnetic compass and the head-up display of the radar must be used for steering.
3. Only after the directional motion of the vessel is under control and there is enough water around the vessel is the second gyrocompass to be connected to the system.
4. The autopilot is switched on only after it is verified that all displays are operating correctly.

The FINNFELLOW sailed through the narrow Hjulgrundet strait 20 minutes before the accident. The strait is only 90 meters wide. Had the compass fault occurred there and transmission of the compass heading been disconnected, the radars would have suddenly jumped to HEAD-UP. This would have proved dangerous at this location. A jammed STEP signal would not have presented the same danger.

2.3.5 Retrofitting of systems

Renewal of old or obsolete systems is part of the technical protective process. During the investigation it became obvious that retrofits can create new problems. In the tests performed after the grounding, radio frequency interference was clearly found to cause operational errors in gyrocompasses of the Standard 20 type on several ships.

The gyrocompasses on the ships that were tested had been installed as retrofits, in which case it is normal to utilise the existing cables whenever possible. In these installations it often happens that the cable types, their interference shielding, and the cross-sections of the wires are not suitable for the new equipment fitted.

Summary of the failure of the protective systems. On the FINNFELLOW, the protective systems failed. The compass system is usually constructed in such a way that it relies, in practice, on only one compass, even when it contains more than one. In this type of system either of the heading signal fault modes described above is dangerous. A compass failure always creates a hazard.

The grounding of the FINNFELLOW has demonstrated that standardisation of the compass signals is required.

2.4 Shielding against interference

2.4.1 Shielding against interference after the accident

After the grounding of the FINNFELLOW, Raytheon took action to eliminate the effects of radio frequency interference. The interference shielding of STANDARD 20 gyro compasses has been improved in retrofits on several ships in the following ways:

1. The wires earthing the instruments in the compass system were made as short as possible (this is not a requirement in the manufacturer’s installation instructions).

2. All cable shielding was earthed if possible.

3. The coiled surplus part of the cable connected to the gyrocompass was removed.

4. A metal net was installed on top of the gyrocompass base plate and connected to the gyrocompass casing.

5. The air intake for the fan on the gyrocompass casing was protected with a metal net which was earthed with self-adhesive copper foil to the casing itself.

6. The rubber seal on the side of the gyrocompass lid was covered with copper foil and connected to the gyrocompass casing.

7. Where the maintenance opening of the gyro compass made contact with the casing, the contact surfaces were stripped of lacquer and then covered with copper foil.

After carrying out tests, the above actions were found to be sufficient for eliminating the effects of radio frequency interference on the operation of the STANDARD 20 gyrocompass.

2.4.2 Testing for interference on board ship

The investigation has shown that testing for interference in a laboratory is necessary. However, the cabling, earths and installation conditions which exist on board ship have a crucial effect on the way the system reacts to interference, and these conditions cannot be duplicated in the laboratory. It is not sufficient to perform tests only in the laboratory.

Therefore, the effect of electromagnetic interference on the operation of the gyro- compass must also be tested in connection with the installation and implementation of the equipment on board the ship. The tests should be performed using interference frequencies and field intensities that may be encountered in seafaring.

2.5 Protection of the navigation system

The protective systems fitted, which adhered to current maritime culture, failed in the grounding of the FINNFELLOW. Section 2.3 described traditional protective systems for ensuring the reliability of the compass. Section 2.4 dealt with the shielding of the compass against radio interference. The navigation system must be protected in such a way that the heading is still received by other equipment even if the traditional protective system of the compass fails. It would be safer to use two compasses with different operation principles instead of two identical ones.

The navigation equipment can be protected by connecting a rate-of-turn gyro to the autopilot and by using a Kalman filter. In addition, a compass based on the free-directional gyro can be included in the navigation system. These methods are commonly known but they have not been adopted because neither the users nor the regulations stipulate their use.

2.5.1 Gyrocompass and the rate-of-turn gyro

The rate-of-turn gyro was connected to the first autopilots that had been designed for navigation in the archipelago. The idea was to combine the rate-of-turn autopilot for river traffic (Rate Pilot) and the conventional autopilot based on the maritime gyrocompass. A vessel then turned with the rate-of-turn gyro and the straight passages were steered with the gyrocompass[23].

The combination offered one advantage over the gyrocompass alone: any malfunctions in the compass could be monitored with the rate-of-turn gyro. If the gyro-compass was operating irregularly, the autopilot gave an alarm to indicate that the operation of the compass did not correspond to the reading of the rate-of-turn gyro. The autopilots became less reliable in the 1980s when the rate-of-turn gyro was relinquished because of cost factors, and the rate of turn was differentiated from the gyrocompass heading. This has become standard practice in the navigation industry. The operation of the gyrocom-

[23] Hagelstam, Larjo, Sten 1976

pass is monitored only by the compass system itself. An important protective mechanism had been lost.

2.5.2 Kalman filter

If a fault situation arises in integrated navigation, it is difficult to detect which part of the equipment is malfunctioning. The disappearance of the heading or the speed data is currently the greatest risk factor in integrated navigation.

The transmission of the heading to the rest of the system can be ensured with a Kalman filter, even in the event of a compass malfunction. The Kalman filter first predicts the future heading values for all the sensors that indicate heading and then compares these to the detected values. The values with the most deviation are excluded and the sensors are assigned reliability coefficients. Finally, the values are compared with each other and the most reliable directional estimate of the headings indicated by all the sensors is transmitted to the navigation equipment.

The following sensors can be used as sources of heading information:

- Gyrocompass complying with IMO regulations. In integrated navigation, it is not enough to correct only the speed error. The best accuracy is obtained if ballistic correction is used.
- Magnetic compass (Transmitting Magnetic Compass, TMC) with integrated correction of magnetic variation and the deviation curve.
- Course Over Ground received from the DGPS corrected by the drift angle from the Doppler log.
- Free-directional gyro updated by the Kalman filter.
- GPS compass filtered and stabilised by the inertia of the free-directional gyro.
- Rate-of-turn gyro.

The use of the Kalman filter prevents the jamming or loss of the steered heading caused by the disappearance of only one heading. If there is a malfunction in the gyrocompass, the Kalman filter provides an alarm and the system is able to calculate the heading based on other sensors. The Kalman filter can be used to ensure the redundancy of two compasses.

2.5.3 Use of the free-directional gyro as a compass

The wording of the IMO resolutions on gyrocompasses refers to a compass that aligns itself towards the north according to the rotation of the earth. Present technology provides the opportunity to use other more accurate solutions.

Text books on the **gyrocompass** mention that a gyrocompass aligning itself to the north according to the rotation of the earth is suitable only for slow vehicles such as ships[24]. Ships do not move slowly these days. Also integrated navigation has raised the accuracy requirement of the compass beyond that of the IMO recommendations. In practice, the accuracy must remain within one degree.

The free-directional gyro is suitable for vehicles travelling at high speed which make quick turns. In aircraft the directional gyro is used to filter the fluxgate magnetic compass which is prone to interference. In terrain vehicles which need accurate headings, the updating of the directional gyro is done with terrain targets and a map. Technical progress today has made it possible to use the directional gyro in marine navigation also, since precise positioning techniques provide an accurate heading reference.

The directional gyro is technically simpler than the gyrocompass. The directional gyro maintains its direction with regard to outer space. Any variation in the heading and speed of the vessel do not affect the directional gyro. A clock is integrated to the directional gyro for turning the gyro with the rotation of the earth 15° x sin(latitude) per hour. The gyro maintains its direction with reference to longitude but it does not have a north-seeking quality. A directional gyro in good order drifts about one degree per hour so regular updating is needed.

Regulations. On a conventional ship, the directional gyro is not considered to be a compass as stipulated in the SOLAS convention[25]. The IMO regulation on fast vessels (High Speed Craft-Code, HSC) stipulates that the compass must be sufficiently accurate to meet the steering properties of a high speed craft[26]. This can be interpreted in such a way that the HSC code indirectly approves the use of the directional gyro. The code sets the practical need as the determiner of the accuracy requirement. However, the technical requirement for the compass in a high speed craft that followed the code does not realise this specification since it[27] was still based on the 1979 compass resolution. The IMO has not yet defined the accuracy requirements for a compass which is connected to integrated navigation equipment.

The IMO resolution on compasses refers to a compass that aligns itself with the north with the help of the earth's rotation and gravity. The resolution on gyrocompasses states in the introduction that the compass should determine the direction of the ship’s head in relation to the geographic north[28]. The definitions stipulate that the gyrocompass shall comprise the complete equipment and include all essential elements of the complete design[29]. A compass based on the directional gyro would comply with the rules if the

[24] Machover vol.2, pp.1-98

[25] IMO, res.A.424(XI) 1979. The accuracy definitions of the regulation refer to a compass turned to the north by precession based on gravitation, par.5.2.

[26] IMO, HSC CODE 1995 Chapt.13, par.13.2.6: "be provided with a gyro compass which should be suitable for the high speed and motion characteristics and area of operation of the craft".

[27] IMO res. A.821(19) 1995.

[28] IMO Res. A.424(XI) 1979, par.1.

[29] IMO Res. A.424(XI) 1979, par.2.1.

north-seeking part of it formed a uniform entity with the gyro. The High Speed Craft code refers more to the directional gyro than to the gyrocompass[30].

Tests on the directional gyro. Tests were performed on a Siemens directional gyro[31] in archipelago traffic in 1989. The gyro had been on a German aircraft in 1944. The tests showed that the accuracy of the Siemens directional gyro to within 1°–2° an hour was comparable with that of a modern gyro. The direction of the gyro was updated manually once every hour.

The tests on the directional gyro were continued in 1991 on the TELDIX directional gyro designed for land vehicles. The gyro included a processor that changed the correction coefficient of the gyro after each adjustment of the direction. The TELDIX gyro drifted only 0.25° per hour in archipelago conditions.

The tests proved that the directional gyro worked technically, but the heading update should have been automatic.

Automatic direction correction can be realised by measuring the direction by satellite positioning. A GPS compass has three or four antennae at a distance of about one metre from each other. The direction is calculated on the basis of the phase difference of the radio wave. A kinematic measurement method using two GPS receivers has reached an accuracy of 0.2°[32]. At least one satellite compass system suited for merchant vessels is already on the market.

The heading of the directional gyro can be automatically updated at regular intervals through the satellite navigator. Even if the satellite signal breaks off, the directional gyro continues to relay the direction to the autopilot. This idea has not gained ground, presumably because the GPS is a system of the US Department of Defense. A compass complying with the rules must rely on the jurisdiction of civilian authorities. The European Union's GALILEO satellite system will be completed in 2008, according to the latest information[33]. The development of the new compass system could proceed in parallel with the development of the GALILEO.

[30] IMO HSC Code, Res. MSC.36(63) 1994. Chapter 13, par.13.2.6.
[31] Kurskreisel Bauert SAM-LKü4.Gerät.no.127-210 A-2. Werkstelle Siemens Apparaten und Machinen.
[32] PILOTMATE, ARINC Inc. 1998. PILOTMATE, A GPS based accurate positioning and Heading system.
[33] GALILEO Get Go-Ahead (?), NAVIGATION NEWS Nov/Dec.2000,
Magazine of the Royal Institute of Navigation

3 CONCLUSIONS

An integrated navigation system must have access to geopgraphical position, heading and speed. An unexpected loss of the position sensor resulted in the grounding of a vessel on the east coast of the United States in 1995[34]. A loss of speed sensor caused a grounding in the Swedish archipelago the same year[35]. The jamming of the compass heading caused the grounding of the FINNFELLOW.

Nowadays the information relating to the position of the vessel is reliably transmitted from the satellite navigator to the integrated navigation system, but the transmission of the heading and the speed is not completely reliable.

3.1 Technical chain of events

- On the FINNFELLOW the gycrocompass heading follow-up jammed when the indicated temperature of the gyro fluid dropped below 45°C and caused the compass to go into its HEATING status as a result of radio frequency interference.
- No alarm was given, although the heading information to the autopilot was increasingly false.
- The HEATING status did not cause an alarm because it was a normal status according to the system logic.
- The differential alarm between the gyrocompasses was not active during the HEATING status, or otherwise, if one of the compasses was malfunctioning.
- The heading information (STEP output) jammed during the HEATING status and the compass system sent false heading information to the autopilot without causing any alarms on the bridge.
- The flow of the heading information from the gyro sphere was cut off as designed in the programmed logic. The heading information to the radars and autopilot in the navigation system got stuck at the same reading for 67 seconds.
- The FINNFELLOW was making a 50° turn to starboard steered by the autopilot when the HEATING status was activated. The jamming took place 2.5° before the end of the turn.
- The autopilot continued to finish the turn to starboard according to its logic. The system increased the rudder angle to starboard since the heading reading it received did not change.

This technical chain of events caused the accident.

[34] National Safety Board, Grounding of m/s Royal Majesty, 10.6.1995. http://www.ntsb.gov/Publictn/1997/MAR8701.htm

[35] Accident Investigation Board Finland, Grounding of M/S Silja Europa, Accident Investigation Report 1/1995, page 67

3.2 Activity on the bridge

- The conditions for an accident were created because there was no alarm.
- The actual passage of the ship could not be seen on any of the navigation displays. The pilot, who was steering the ship, and the officer of the watch did not realise that the autopilot had increased the rudder angle to starboard.
- The officer of the watch noticed on the radar that the compass was not functioning correctly.
- The corrective actions were initiated too late because the fairway passed too close to the shore.
- Despite the corrective manoeuvre and the attempt to stop, the FINNFELLOW went aground at a speed of 14 knots, one minute and thirty seconds after the jamming of the compass signal.

The crew on the bridge were powerless to stop the technical chain of events that led to the accident because there was too little time.

3.3 Collapse of the gyro protective system

Mechanically, the navigation system and the gyrocompass functioned correctly on the FINNFELLOW. Even the gyro program, although it contained a flaw, operated as designed. The failure of the protective system allowed the malfunction caused by the radio interference to start the chain of events leading to the accident.

Regulations do not require automatic verification of the heading data used by the autopilot in the case of a malfunction in the gyrocompass giving the heading, or if the heading follow-up gets jammed. The directional error of the FINNFELLOW in the grounding situation exceeded the maximum error of 2.5° allowed by the IMO regulations by a fair margin, in other words the error should have caused an alarm on the bridge.

The IMO resolution demands electromagnetic shielding and a sound alarm in a fault situation, but these demands did not provide sufficient protection in spite of type approval and annual surveys of the equipment. The regulation is too general and this results in weak protection.

In type approval tests the gyrocompass was only tested with radio frequency interference up to 300 MHz. Radio frequencies around 450 MHz, 900 MHz, 3 GHz, etc. were not tested at all, in spite of these frequencies being in common use in maritime systems.

Operation and software versions of the compass system. The compass system of the FINNFELLOW sent false heading information to the autopilot during the HEATING status without any kind of an alarm indication on the bridge. The heading information (STEP output) jammed during the HEATING status. The operation of the STEP output depends on the software version of the gyro compass.

The differential alarm did not function. A software version that jammed the heading follow-up during the HEATING status was installed in the gyro compasses. According to the gyrocompass manufacturer, the HEATING status was a normal status. The differential alarm between the gyrocompasses was not operating during the HEATING status. There are several other statuses in the compass system that disable the differential alarm. The differential comparison could not fulfil its task. The regulations do not require a differential alarm for the compass. However, the officers expect it to work if one is installed on board the ship.

Alarm on the false heading. A break in the transmission of the compass heading or a jamming of the heading information always creates a serious emergency. A malfunction in the compass, or in any other equipment in the navigation system, always causes a hazard when steering on a narrow fairway. The situation becomes more serious if no alarm is received of a malfunction in the equipment, as was the case on the FINNFELLOW when the compass heading froze for more than a minute at its old reading. False heading information must always result in an alarm, but even the false heading information must nevertheless be transmitted to the navigation system unless the compass is automatically changed.

Renewal of equipment is one part of the protective system set up to improve safety. The retrofits strive to utilise as far as possible the existing cabling of the ship. This leads to using cables that do not have the interference shield and/or wire cross sections required by the manufacturer. The earths in the cables and earthing of the equipment may also be deficient. Incomplete testing of the equipment may cause further risks. Old unshielded cabling was used on board the FINNFELLOW almost exclusively from the control unit of the compass system to the repeaters in the steering gear compartment and to both wings of the bridge.

Installation instructions. The manufacturers of compasses, speed sensors and positioning devices should provide extensive and clear instructions for their installation in order to guarantee the operational reliability of the equipment. The installation instructions must also cover connections made to equipment from other manufacturers. The cabling and connection drawings of retrofits should be sent to the equipment manufacturer for approval. A representative of the equipment manufacturer should also verify the need to renew the cable network.

Maintenance has a central role in the upkeep of the operational shape of the equipment and the safe navigation of the vessel. When a malfunction arises in a piece of equipment or a system, the reporting of the problem for maintenance and its subsequent repair is no guarantee that the real cause of the malfunction will be found.

For example, the recurring heading errors in the gyrocompass on the FINNFELLOW were rectified by changing the gyro fluid and the gyro sphere. There is a possibility that these heading errors could have been caused by radio interference. Similar compass heading errors have occurred when testing with radio frequency interference.

Maintenance reports should also be sent to the equipment manufacturers in order to provide them with an opportunity to react if the detected faults appear abnormal.

Documentation, user manuals, descriptions of how equipment operates, and cabling and connection drawings must always be kept up to date on the ship. The gyrocompass documentation on board the FINNFELLOW did not include information on how the heading information behaves during the HEATING status.

If there are changes to the system and its software, all users must be informed of these. The user manuals must also be updated.

3.4 New protection methods for the navigation system

The Maritime Safety Department of the Finnish Maritime Administration mentioned in its statement on the FINNFELLOW investigation report that it is recommendable to use best available technology in ships that regularly navigate in difficult archipelago fairways.

Shielding the compass system against radio frequency interference is not enough. The heading information for the navigation system must be further protected by solutions based on different operational principles. Connecting a rate-of-turn gyro to the autopilot, using a Kalman filter and a compass based on the free-directional gyro are commonly known but they have not been adopted.

The rate-of-turn gyro has not become very popular in navigational autopilots, even though the rate-of-turn information is required. It has become the practice not to use a separate rate-of-turn gyro since the rate of turn can be differentiated from the gyrocompass heading. An important safety factor has remained unused because the autopilot cannot compare the operation of the gyrocompass with the rate-of-turn gyro. A rate-of-turn gyro connected to the autopilot would verify the correctness of the gyrocompass heading and would give an alarm, if necessary.

A Kalman filter is necessary in integrated navigation since uninterrupted flow of the speed and heading information must be ensured. False information from one heading sensor must not affect the entire system. The Finnish Maritime Administration proposed the use of the Kalman filter to the IMO in 1998[36]. The grounding of the FINNFELLOW demonstrated the importance of this proposal.

The directional gyro as second compass. The IMO accuracy requirements for a conventional gyrocompass are not sufficiently stringent for its use in marine integrated navigation. It would be safer for a ship to use two main compasses with a different operating principle than two identical compasses. The alternative compass could, for example, be based on the principle of the free-directional gyro, which is updated automatically using satellite techniques.

[36] Operational and Design Standards for Integrated Bridge Systems, IMO, NAV 44/INF.3 24 April 1998. Par.4. 'Ship's heading shall be derived with Kalman filtering techniques'.

4 RECOMMENDATIONS

4.1 Improvement in the operational reliability of the gyrocompass

The manufacturers of compasses, speed sensors and positioning equipment should provide extensive and clear installation instructions to guarantee the operational reliability of the equipment. These instructions should also be provided for retrofits. The manufacturer should also issue requirements for shielding against interference and for the cross sections of the cabling. In addition, guidelines on the earthing of cables and devices are needed. The installation instructions should also cover connections made to equipment from other manufacturers.

The gyrocompasses should be shielded against electromagnetic interference as stipulated in the IMO resolution A.424(XI) Section 7.1. The implementation of this rule can be supported by performing radio interference tests on vessels so that any possible problems arising from the installation can be eliminated.

The operational specifications and user manuals for equipment on board ships should be kept up to date. Current drawings on the location of the instruments and on the installation and its cabling are also needed for maintenance. Any changes to the equipment must also be approved by the authority which performed the type approval testing.

It is the recommendation of the investigation board that the gyro compass manufacturers

1. *Include verification of the location of the instruments and of the cabling in the installation instructions of their equipment so that the effects of electromagnetic interference could be eliminated.*

The investigation board recommends that the equipment manufacturers and authorised representatives

2.. *Test the effect of electromagnetic interference on the operation of the gyrocompass on board the vessel also in connection with the implementation of the equipment using interference frequencies and field intensities occurring in maritime traffic.*

3. *Check and update the instructions, operational specifications and other documents on board after modifications have been made to the equipment or installations. These documents should also be sent to the authority in charge of type approval for the equipment.*

4.2 Improvement in the operational reliability of the navigation system

The autopilot needs the rate-of-turn information to fulfil IMO requirements[37], since the regulation requires that turns be executed at a pre-set rate of turn or turning radius. In practice, the rate of turn is differentiated from the compass heading, which is hardly the purpose of the regulation. The IMO regulations do not require a separate rate-of-turn gyro, which could be used to monitor the status of the gyrocompass. The modification should be added to the IMO guidelines on the autopilot and its alarms[38].

It is the recommendation of the investigation board that:

4. *the equipment manufacturers facilitate the connection of a rate-of-turn gyro to the autopilot. The rate of turn should be compared to the rate of turn differentiated from the gyrocompass heading.*

The Kalman filter can be used to protect the navigation system against sensor faults. Finland has proposed to the IMO Safety of Navigation subcommittee that the Kalman filter be used in integrated navigation systems. This would ensure the correct compass heading and speed for the autopilot at all times.

The investigation board wishes to bring the following to the attention of the manufacturers:

5. *In the IMO, the regulations are handled for safeguarding integrated navigation. In the proposal, the heading and speed used by the autopilot must be received through a Kalman filter.*

The IMO gyrocompass regulation has limited the development of the gyrocompass to a system based on gravity. Current technology allows the development of an accurate compass with a free-directional gyro, updated automatically by a satellite system, to be realised.

The High Speed Craft Code of the IMO requires that there be a sufficiently accurate compass on board the ship with regard to the traffic she is intended for. Since the minimum accuracy requirement in the IMO regulation on the gyrocompass is in practice inadequate for integrated navigation, Finland has proposed to the IMO Safety of Navigation subcommittee that a compass based on the principle of the free-directional gyro be allowed in connection with integrated navigation equipment[39] in accordance with the principles of the IMO High Speed Craft Code.

The investigation board wishes to bring the following to the attention of the manufacturers:

[37] IMO, Res. MSC.64(67), 1996. Annex 3,par.3.2
[38] IMO, Res. MSC.64(67), 1996. Annex 3,par.6.2
[39] Operational and Design Standards for Integrated Bridge Systems, IMO NAV 44/INF.3 24 April 1998 par.4 , 'A directional gyro can be used instead of a north seeking gravity gyro compass. The direction gyro shall be north stabilized with magnetic or position sensors.'

6. *In the IMO, the regulations are handled for safeguarding the compass heading used in integrated navigation and the improvement of its accuracy. It is proposed that a compass operating on the principle of the directional gyro be allowed as an alternative compass in connection with an integrated navigation system provided that the direction of the gyro is updated automatically with a positioning device.*

Helsinki, November 27, 2001

Martti Heikkilä | Heikki Tissari

Per-Olof Karsson | Kari Larjo

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