Evaluation of the Multi-site Differential GPS System Multifix Onboard the Hydrographic Vessel L'esperance

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At the beginning of this study, in 1996, differential GPS was reserved to a limited community which had the necessary financial and technical means to be able to use it. Aside from the reference stations transmitting corrections in HF (HF station of the Veripos network), two world-wide systems transmitting corrections by Inmarsat were established, Skyfix and Starfix.

Today, transmitters of differential corrections are continuously expanding, and offering services to a large public, with the coverage of land surface, and the affordable price of DGPS and receiving equipment (including subscription for corrections). Note the services using 'geostationery' communication spot beam satellites, such as Landstar (RACAL) and Omnistar (FUGRO), the transmissions in MF (285 to 325 kHz) near the coasts, and finally the transmissions through MF digital radio (RDS). These new developments unfortunately do not cover the large oceanic areas, for which the reference stations are far away, and the transmitters are expensive and of limited availability.
This study only concerns single frequency receivers (GPS) in degraded mode (SPS). The differential corrections are corrections of pseudo-distance, used in quasi real time. Long range systems are also studied (LRDGPS Long Range Differential PGS).

From now on, we will call single-station DGPS, systems using differential corrections from only one reference station to calculate the point, single-reference. Various methods are possible, depending on the information carried by the differential correction messages (format RTCM 104 V2 and 'Sercel' are used by the SHOM), depending on the availability of other information than the navigation messages from the GPS satellites, and depending also on the degree of sophistication of the algorithms.
A multi-reference DGPS system uses differential corrections from several stations to calculate the point. Here again, several types of systems exist:

- Several single-reference solutions are calculated from the corrections received from each station, the final point being a barycentre of the solutions
- All the differential corrections received allow the calculation of points of which the intersection gives the point (This is the case for Multifix)
- Optimised corrections leads to the calculation of an approached location, calculation of the point is then analogue to a single-station

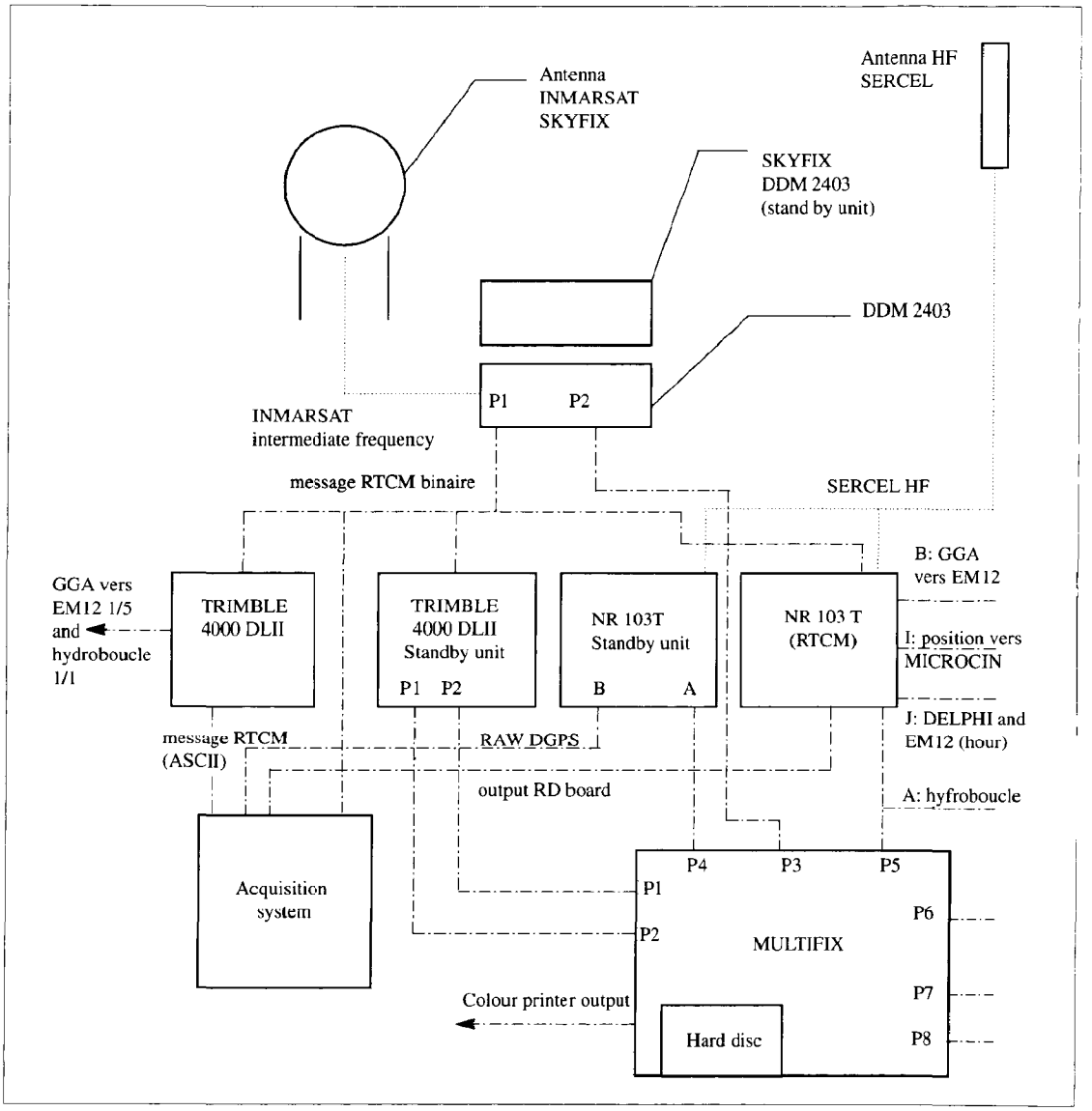

Figure 1: Connection of the GPS elements with other equipment

For this last method, the optimised correction can be calculated onboard the mobile vehicle (case of the VBS coupled to the Starfix system of FUGRO), or on land (virtual stations gridding (Landstar) and possibly zone model).

Brief Description of the Multifx

Multifix is a multi-differential positioning system, comprising a source (3 at the maximum) of differential corrections in the RTCM 104 (version 1 or 2) format, a 'demodulator' and 'decoding' RACAL DDM2400 of Skyfix corrections. A slave GPS receiver provides the raw GPS data (data in), through a simple link, as well as the time and the nautical almanac provided through a bi-directional link (RCI: remote control interface). The slave GPS receiver can calculate a position, possibly differential, which is then provided to Multifix through the link DATA IN.

The computer support needs a powerful computer (here a PC Compaq Pentium 90 MHz) having a RS232 8 outputs board, and a COM output and parallel output. The software version is the 2.08 c, which has been provided during the training session.

Completely Autonomous Differential GPS

Being first a differential GPS, Multifix is able to calculate solutions for positions (6 solutions maximum), and to provide them in a very short time (1 to 2 sec) to the various equipment, which need them in a variety of formats and even in different geodesic systems. A differential solution is calculated from a group of reference stations, a group of 1 to 8 stations, chosen by the operator. Other solutions can be inspected, such as the calculated point in natural mode, the calculated position from the slave GPS (in natural or differential mode), or the position of another system received from the 'monitoring' input. For the same group of reference stations, the operator has the choice between the traditional 3D+T mode, or a hybrid mode 2D+T called 'alt aiding', which uses the relatively fixed altitude of the mobile over the geoïd as a supplementary constraint for the point calculation. This mode is only possible with the use of geoïd models denser and more precise (OSU91A) than the ones used in classical GPS receivers (NR103 or Trimble 4000 DLII). The number of differential stations should not exceed 12.
Once initialised and configured, Multifix does not need any operation, and the system can even function with the monitor and key board disconnected.

The Configuration

Most of the configuration parameters are set during the installation, and will never be later modified by the operator. Essentially, they are the configurations of the digital links, the chosen formats of the messages and of the serial port parameters.

Performances

Reference Position

The most precise positioning system used in deep-sea navigation onboard the *Esperance* is the GPS receiver NR103T from Sercel, using the Sercel HF corrections (this same receiver accepts corrections in the RTCM104 format). The two reference stations used during the evaluation are the one on Santa Maria (SM), which is an island at the south-eastern end of the Azores archipelago, and the one on Cabo Raso (CB), which is a cape located 30 km north of Lisbon, Portugal. These two stations belong to the SHOM and have been very accurately positioned by spatial geodesic methods in a world-wide system. Targets in

location	station	radius 95%	radius 99%	error	bias
Ponta Delgada	SM 100km	1.2 (1.1)	1.5 (1.5)	0.1 (0.0)	<1 m
Horta	SM 300	1.3 (1.1)	2.0 (1.5)	0.2 (0.1)	<1 m
Funchal	CB 950	4.5 (2.2)	11.7 (3.8)	4.3 (0.4)	<2 m

Table 1: Values in parenthesis are results coming from Sercel quality of points

Station 1	Station	radius 95%	radius 99%	error >5 m%	% rejected (q<9)
SM 450 km	CB 900 km	2.7	3.2	0.2	10%
SM 800 km	CB 1000 km	2.7	3.4	0.3	25%
SM 300 km	CB 1700 km	3.2	4.2	0.4	30%

Table 2: Dynamic (moving) targets

Station 1	Station	rayon 95%	rayon 99%	deviation >5 m%	% rejected (q<9)
SM 100 km	SM 100 km	0.8	1.2	0.0	0.5%
SM 400 km	SM 400 km	1.0	1.5	0.0	0.3%
SM 750 km	SM 750 km	1.3	2.4	0.2	6%

Table 3: Dynamic targets with the 2 receivers on Santa-Maria

diurnal ranges, positioned during the past years, and during the evaluation period, have all shown a great precision in position, of the order of 3 to 4 m at 95 per cent, extended to 2 to 3 m at 95 per cent when the very reliable quality criteria reaches the value of 9. Considering today's satellite constellations, with an 'altitude shadow' of 5°, and a threshold value of 10 for the GDOP at 3D/2D transition, and at less than 500 km from the stations, the quality of 9 is estimated as over 98 per cent point quality.

- Static targets

Values in parenthesis are results using only Sercel quality 9 points.
Values are calculated at the gravity centre of the target, the estimated deviation is the difference between this mean point and the real, unknown, position. Due to the lack of geodesic measurements, the deviation can only be estimated by coherence analysis between the targets with different reference stations (HF Sercel and Skyfix, and the probable degradation away from the reference station).

- Dynamic targets (quality 9)
- Dynamic targets, two receivers on Santa Maria (quality 9)

Performance of the NR103 RTCM

The following table shows the targets obtained in dynamic mode (couple of stations) or in static mode. The reference stations are indicated by 2 letters. The static target are noted 'quay'.
Dispersion in the RTCM mode is slightly greater than the one resulting from the HF mode, which is mostly explained by the close positioning of the Sercel HF stations. Both types of corrections have similar characteristics (delay, refresh rate). With equal refresh rate, the Sercel format allows a smaller digital flow than the RTCM.

	28/05 CD	29/05 SM/ CD	30/05 CB/ CD	31/05 CB/ CD	04/06 CB/ CD	05/06 CB/ CD	15/06 CB/ CD	07/10 quay CD*	22/10 quay CD	23/10 quay CD	30/10 quay CD
95% (m)	3.14	2.09	3.06	2.81	2.90	2.45	2.50	1.22	1.70	1.51	1.62
99% (m)	3.74	2.73	4.18	3.62	4.66	3.13	3.30	1.62	2.46	2.63	2.38
>5m (%)	0.07	0.13	0.38	0.01	0.84	0.12	0.29	0.00	0.01	0.21	0.05

Table 4: Performance of NR103 single-reference position

Performances of the Multifix

Two types of solutions have been particularly analysed in the zone of Azores:

- A is the multi-reference solution using the nearest Skyfix stations (6 stations): Scillies, Cadiz, Den Helder, Aberdeen, Flamborough and Halifax
- B is the dedicated solution to simulate the functioning of Multifix under the most unfavourable conditions, when the stations are farther than 2500 km: Aberdeen, Flamborough, Den Helder, Halifax, and Rome

In addition to these solutions, trials have been made on the nearest single-reference station, to compare with a solution and with NR103 of RTCM solution on the same station.
Last, a very long distance C solution (>4000 km) has been analysed during mission 96.2: Cairo, Nigeria, Hammerfest, Tampa.

Sessions	solution	27/09	28/09	01/10	05/10 quay	06/10 quay	20/10	23/10 quay	25/10	30/10 quay	31/10 quay
95% (m)	A	3.12	2.19	2.66	3.56	4.15	2.48	3.41	2.50	2.26	3.06
99% (m)		3.63	2.71	3.40	5.18	6.19	2.95	4.96	2.94	2.98	5.78
>10m (%)		0.00	0.00	0.00			0.00		0.00		
95% (m)	B	3.29	2.33	2.79	3.68	4.25	2.57	3.78	2.69	2.47	3.46
99% (m)		3.82	2.89	3.53	5.53	6.36	3.04	5.90	3.17	3.27	5.83
>10m (%)		0.00	0.00	0.00			0.00		0.01		
95% (m)	C	3.05	2.83	3.13			3.97	3.00	2.98	3.37	4.21
99% (m)		3.72	3.71	3.99			4.58	4.59	4.16	3.99	5.86
>10m (%)		0.00	0.00	0.02			0.12		0.00		

Table 5: Performances of Multifix multi-reference position

The various performances of Multifix solutions are presented in the table above. The two chosen criteria are targets dispersions of 95 per cent and 99 per cent. The variations greater than 10 m are given in per cent. The reference used is the NR103 for the dynamic targets (Santa Maria), the term 'quay' is given to the static targets. This table shows:

- A good coherence between the two DGPS (Multifix and NR103 HF in quality 9), the position divergence is less than 5 m in 99per cent of the cases
- Dispersion of the dynamic targets is slightly smaller than for the static targets, which can be explained by the possible correlation of the position error of the two systems, as well as the rejection of points with Sercel quality equal and below 8

These observations being taken into account, the absolute precision of Multifix is of the order of 5 m at 95 per cent, for multi-reference solutions distant up to 3000 km. Precision increases when the stations are nearer (of the order of 3 m at 95 per cent in a area of 1000 km).

Advantage of the Multi-reference Solution

In terms of precision, the interest of the multi-reference solution only appears from 2000 to 2500 km ; below this distance, the single-reference solution has similar performances. For the same reference station, the NR103 RTCM solution offers a slightly smaller dispersion, but also is available with a shorter delay (of the order of 0.5 s) compared to the digital outputs of Multifix of the order of 1 to 2 s.
Sometimes, it is possible to get relatively small dispersions with single-stations (Multifix or NR103 RTCM) at much greater distances (> 3000 km). However, the main origin for the quality degradation is the small number of simultaneously visible satellites, implying that such an application is not possible in operation. In addition, it must be mentioned that the evaluation has been performed during a period of minimum solar activity (cycles of 11 years), and the accuracy of ionosphere delay calculated by models will be degrated.
The Multifix multi-reference solutions are characterised by a small number of aberrant points. The A solution (the nearest stations) has given a percentage of 0.1 per cent for the differences of more than 10 m, compared to the reference NR103 HF. For static targets, differences of the same magnitude appear. Also, it must be mentioned that no rejection criterion has been activated with Multifix.

Quality Criteria

Quality Criteria of the NR103

The main parameters calculated by the NR103, and which can be used as quality criteria are:

- Anterior criteria: DOP (mainly GDOP, HDOP), operating mode,
- Posterior criteria: DRMS, LPME (mean variation of position line), rejected points.

Measurements of position, speed, bearing, and altitude can also be used during the position calculation with hypotheses on the dynamic of the mobile.
NR103 provides a grade for the synthesis quality. The grade varies from 1 to 9, and experience shows that grades 2, 3, 6, and 7 are extremely rare, and only appear during transitory periods or when poor geometry exists.
Experience of many targets carried out during several years shows that the quality grade of 9 allows the discarding of almost all the aberrant points (and to be rigorous, the first point back to 9 after a decrease in quality should also be discarded).
In the case of the evaluation of another positioning system, it would be logical to only consider the points with quality of 9, to make the best of the reference. The threshold of 9 would, on the other hand, be too severe in the case of deep-sea measuring. It can however, be used to classify uncertain points, and to analyse them more precisely during post-processing.
Analysis of some aberrant behaviours of the NR103 indicates that important variations on the position are associated with strong values of LPME. Besides, this criterion, associated with the degradation of the constellation geometry (DOP), is used for large-scale coastal surveys of the MOA (2DRMS=2*GDOP*LPME, if LPME >=1) to quantify the precision on the position. Although there has not been any systematic analysis, it seems that important values of 2 DRMS are frequently associated with important position divergence and reciprocally. In the case of a deep-sea survey, at about 2000 km from the reference station, an alarm threshold of 20 m for the 2 DRMS seems to be adequate. It should still be mentioned that in the unfavourable case of 4 satellites, the LPME is not calculated.

Quality Criteria of the Multifix

Four variables of the RACAL UKOOA message have been recorded: Ftest, Wtest, and the estimates of dispersions (2σ) in latitude and in longitude, as well as the classical variables (PDOP, number of stations, number of satellites).
The UKOOA criteria are determined to provide the following indications to the operator:

- Expected precision (uncertainty ellipsoid 95 per cent or 2σlat and 2σlong)
- The F-test, or unit variance test, to verify the validity of the stochastic and functional models being used
- Automatic discard of a position (Wtest)
- Distance diversion (MDE) or incidence on position (pos MDE), which can result into a shift non detected by the Wtest

Wtest:

In spite of the great number of messages for positions treated (over 1 million), no automatic rejection observed.

Ftest

The number of rejections of the Ftest is generally less than 1 per cent by session, no net correlation has appeared between the position in the port (quay) and the discard by Ftest.

2σlat and 2σlong

To simplify the study the quadratic mean of the two estimators has been calculated (later called σ2D). The reader may find this short cut more easy (uncertainty ellipsoid), but this approach is more qualitative than quantitative.
If a point is considered bad, when the error exceeds 10 m, it can be observed that all the bad points are discarded with a threshold value of 15 m for the error estimator. Some good points can also be discarded.
It is also noted that if the estimator allows the discarding of aberrant points, it does not measure the precision, the 3 solutions have indeed a similar dispersion, with error estimators varying from 1 to 2.

Classical Criteria
The main sources of degradation of the precision are the:

- Lack of differential correction from some of the stations
- Degradation of the constellation geometry

Some of the dynamic targets have been filtered by discarding points such as:
Number of stations<3, or PDOP<7 or σ2D>15 m.
It comes out in this analysis that the majority of points have been discarded because of the PDOP, and then a significant decrease of divergences greater than 5 m has appeared (for discarding of about 1 per cent of the points, divergences greater than 5 m typically from 0.1 per cent to 0.02 per cent).
As for the quality 9 of the NR103, the real time rejection of these points is not quite possible, the number of the eliminated points being to important. These criteria can however be used to filter the position data in order to determine a mean position, or to evaluate a less performing system.

Discarding Criteria of the Muitifix Solution
It is possible to invalidate in real time a calculated solution by Multifix, in function of the previous criteria:
σ2D > threshold 2D
σ3D > threshold 3D
bad Ftest
PDOP > threshold PDOP
HDOP > threshold HDOP
These criteria can be used according for two distinct possibilities. In the first case, the Multifix position solution is used in operation, and it should only be discarded if there is a strong doubt on its validity, in the second case, Multifix is only used in a control position, for example of the NR103 RTCM, and the discarding criteria can be increased to give confidence to the position.
With experience, we can propose, in the first case, a threshold of **σ2D>20 m** and in the second case **PDOP>7 or σ2D>15 m**.

Real Time Watch

Onboard the *Esperance*, there are two DGPS systems, which can provide the calculated position to the navigation computer and to the multibeam echosouder EM12. Once a system is chosen (configuration of the navigation software, and change of the connection for the EM12), one can ask what to do with the data provided by the other system. It comes naturally that the divergence in position can be calculated and inspected in real time, giving then a simple supplementary quality control on the point.

The monitoring Functions of Multifix
Multifix does not allow the direct inspection of a position (lat, long, alt,) determined by another system. On the contrary the monitoring function allow the inspection of positions determined relatively with the reference solution (Dx, Dy, Dz). This function can thus be used to display in a Multifix window, the positions of one or several external positioning systems.

Monitoring Interface
To achieve this function, divergences between the positions of the two NR103 (operational and safety), and the reference position of Multifix must be calculated. The corresponding messages of virtual monitoring can then be elaborated. In addition, these messages integrate information on the NR103 solutions, such as the mode (2D or 3D), the satellites used, the estimated DRMS, etc...
The interface which must have 3 RS232 inputs and an output, is the 4 ports acquisition system described earlier. A simple program in C performs the message acquisitions, their decoding, the divergence calcu-

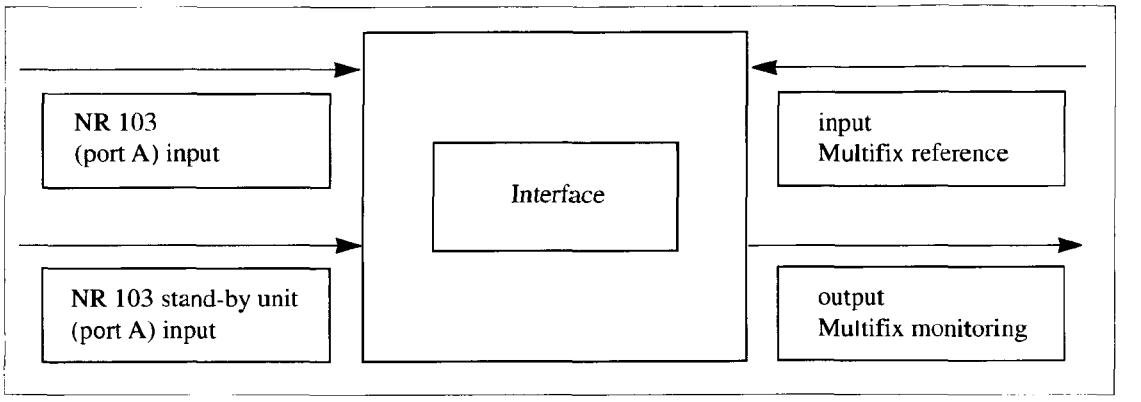

Figure 2: Schematic of the interface designed for real time watch of position

lation, and the format definition for the output monitoring message. No operator is necessary (no screen or keyboard). A sound alarm can be set for divergences between the Multifix reference and the NR103, with a preset threshold of 10 m.

Conclusions

Performance

The calculated co-ordinates of Multifix show a short-term noise clearly stronger, and a more important dispersion, than the calculated co-ordinates of the NR103 in RTCM mode, from the nearest station used by Multifx. This performance degradation is probably due to the lower quality of the pseudo-distance measurements provided by the Trimble receiver 4000 DLII. The precision on the pseudo-distance measurement is estimated at about 2.5 to 3 m (doc Racal and Fugro) on this receiver, against 1 m for more accurate receivers (4000DS) like the NR103. The NR103 antenna is also better situated onboard the *Esperance*, and less subject to multipath.

The NR103 superiority is maintained over 2000 km from the reference stations, and is expected empirically up to 2500 to 3000 km. The use of Multifix permits the value of the MSL of the model OSU91A to be determined, and thus to adopt it onto the NR103 during passes in 2D+T mode, which have been quite usable in operation.

The Multifix solutions use farther reference stations than the main solution, resulting in less accurate positions, but to a small degree, and with no comparison to the increase of the error estimators. However, it should be remembered that the long-distance solutions have been calculated at the same time as the short-distance ones, which may have favoured the adaptative calculation of the weighted measurements made.

An uncertainty zone of 10 m at 99 per cent should be maintained with the network of 3 reference stations, with 2 stations at less than 4000 km, and a satisfactory geometry.

Multifix corresponds well to the need of a fairly accurate positioning system, robust (with a very few number of significant errors), in configuration of long-distance differential stations, when single-reference solutions are not possible.

The study has shown that the limit of 2000 km from the reference station can be exceeded by the NR103, and that even for passes in 2D+T mode, when fewer satellites are simultaneously visible, the point was still valid.

Quality Estimators

Although the UKOOA criteria are theoretically better adapted to estimate the possible degradation of the precision, the difference with the classical estimators is not so obvious. Still, we have observed a good correlation between the high values of the estimators 2slat and 2slong, and the important position errors, this correlation exists on the NR103 between the LPME (or possibly GDOP*LPME) and position errors. The capacity of these estimators to quantify the real errors, even over long periods, is far from being proven.

Usage Policy of Multifix and of the NR103

The NR103 can be maintained as the main navigation system up to 2500 km from the reference station. From 1500 km, it is recommended to calculate the divergence in real-time dynamic mode, between this solution and the best solution calculated by Multifix, and to have a sound alarm for divergences greater than 10 m. Multifix being used as a control system, the discarding criteria can be increased (PDOP < 7 and error 2D < 15 m or 10 m). A simple program has been written to calculate the divergence between the two NR103 and a Multifix reference, and to transmit them to the Multifix in the adequate format (monitoring). Positions of both NR103 can be visualised in a Multifix window, while the positions are calculated.

The NR103 is configured with an elevation shadow of 5°, which may seem small to some specialists, but which has always been satisfactory onboard the *Esperance* in deep-sea surveys. For Multifix a threshold of 7° has been adopted.

This policy may be reviewed in function of the cut rate in the RTCM corrections emission from the nearest station, the NR103 switching automatically to the natural mode after a 30 sec stop, when the multi-reference solution remains valid because of the other stations.

Perspectives

If Multifix is an interesting tool to finely analyse the differential corrections, the point calculation, the constellation, the distance to the reference stations, it ended up being less interesting as a DGPS, so much more than it is limited by the poor quality of the GPS receiver used. Evaluation of Multifix has allowed it to be shown that the limit of 2000 km, commonly accepted as the limit for the single-reference station systems such as Skyfix or Starfix, could easily be extended by the NR103. However, one must admit that the use of several differential stations provides a safety for the survey, by the redundancy of the information, by lesser vulnerability to the cuts, and by the increase in the number of satellites. The ideal would be to keep on using the NR103 as the unique DGPS positioning system, associated to an elaboration system, or a system of reception of optimised corrections for the zone of study. A product elaborated by FUGRO, the VBS (Virtual Base Station) allows this type of use, and experimentation onboard the BO D'Entrecasteaux is satisfying.. This product cannot be adapted to the RTCM format of Skyfix, and requires subscription to the Starfix network (SCF format), which broadcasts information about the satellites in addition to the corrections, thus creating an annoying dependence towards the corrections provider. Multi-reference developments from Sercel (DSNP) are also expected with the NR203.The obvious interest in this product, beyond the probable qualities of the NR103, would be the possibilities of mixed usage of RTCM corrections and Sercel's, which would strengthen the point against the corrections, and would valorise the Sercel stations network (mostly during the night, when the HF range of the stations is increased.

Biography

Jean-Michel Léculier was born in Rouen, France, in 1967. He received the Engineer diploma in electronic engineering from ENSIETA in Brest, France in 1991. Since 1991, he has worked with the Service Hydrographique et Océanographique de la Marine (SHOM), mainly on scientific instrumentation. His previous work deals with acoustic remote sensing (deep multibeam, sub-bottom profiler and seafloor echo analyser), localisation (differential GPS) and vertical reference units. From 1992 to 1997, he was the head of the logictic group, first at Mission Hydrographique de l'Atlantique (MHA) and then at Mission Océanographique de l'Atlantique (MOA). He is currently in charge of acoustic instrumentation (sonar and acoustic receivers,) at the Ocean Acoustic Group within the Center for Military Oceanography, Brest, France.