Argos-3 Satellite Communication System: Implementation on the Arvor Oceanographic Profiling Floats

XAVIER ANDRÉ

Institut Français de Recherche et d'Exploitation de la Mer, Brest, France

BERTRAND MOREAU

Société d'Ingénierie et de Conseils en Technologies, Brest, France

SERGE LE RESTE

Institut Français de Recherche et d'Exploitation de la Mer, Brest, France

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ABSTRACT

The scientific community observes the ocean for applications in the fields of oceanography and climate research. To recover in situ data, more than 3000 profiling floats are operated in the framework of the Argo program. Each float performs cycles between the sea surface and a depth of 2000 m. Scientific data are gathered while the float is traveling upward from the depths of the oceans and are then transmitted via a satellite communication system at the end of each cycle. During its time at the surface, mainly dedicated to transmissions, the float is vulnerable and subject to drift, which limits its use in many studies. Moreover, transmission times are becoming longer due to a trend toward high-resolution or multisensor profiles. Consequently, the transmission system embedded in the profiling floats had to evolve.

Argos-3 is the latest generation of the Argos satellite communication system. It has been designed to allow instruments to transmit more data in a small time budget and as an alternative to Iridium, already implemented on profiling floats in restrictive applications.

This study aims to evaluate the implementation of *Argos-3* on Arvor profiling floats. Tests were carried out first in the laboratory, before being implemented on the Arvor float and deployed at sea. This study proves that the high-data-rate mode suffered from European electromagnetic noise, which is incompatible with this application. The interactive low-data-rate mode was successfully qualified; it is capable of transmitting an entire dataset in a few minutes, compared to 8–10 h for the previous *Argos-2* system.

1. Introduction

The Institut français de recherche pour l'exploitation de la mer (Ifremer) develops and operates the Arvor and Provor oceanographic profiling floats within the framework of the Argo international program. This project aims to maintain a fleet of 3000 instruments at sea and to monitor the temperature and the salinity of the upper 2000 m of the ocean in near–real time (Fig. 1). The data are used as input for scientific numerical models, related to the knowledge of the global ocean and its evolution in time and space (Roemmich et al. 2009; Freeland et al. 2010).

The market for profiling floats is constantly changing, as it must meet the growing challenges of the scientific community. As a result, float technologies have to evolve as well and particularly the satellite communication system used to transmit the data, which is the key element in many aspects.

First of all, floats currently need to transmit more data in order to increase the sample rate of the Argo profiles or to meet the growing scientific demand to embed additional sensors on profiling floats (D'Ortenzio et al. 2010). For example, the Provor family now includes a

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Corresponding author address: Xavier André, Ingénierie et Instrumentation Marine, Recherches et Développements Technologiques, Ifremer, Z. I. de la Pointe du Diable, CS 10 070, 29280 Plouzané, France.
E-mail: xavier.andre@ifremer.fr

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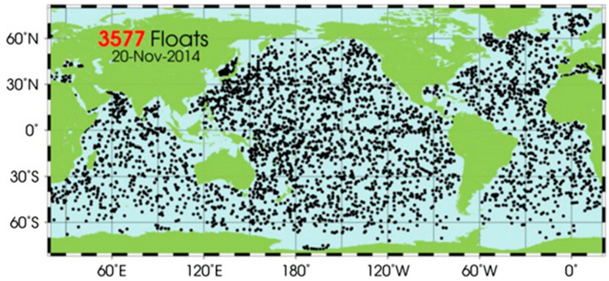

FIG. 1. Active Argo oceanographic profiling floats on 20 Nov 2014.

nitrate sensor on the Provor ISUS float (D'Ortenzio et al. 2012) and dissolved oxygen and other biogeochemical sensors on the ProvBIO floats (Le Reste et al. 2009). The transmission of such quantities of data is not possible via the current *Argos-2* communication system.

Furthermore, the Arvor float with the *Argos-2* system spends a long time at the surface transmitting its data. It is thus vulnerable to biofouling, which affects the quality of its measurements, or it can be hit and destroyed (Le Reste and André 2011). Moreover, winds and surface currents cause the float to drift during transmissions, which makes it difficult to estimate the drift of deep-water masses (Park et al. 2005), because the trajectory and current speed at the parking depth cannot be accurately determined. This also reduces its use in closed seas, where the risk of beaching is high. For example, the transmission of a typical Argo profile—that is, about 100 conductivity–temperature–depth (CTD) samples over a range of 2000 m—takes 6–8 h via the *Argos-2* system to guarantee a good reception rate (Le Reste and Gould 2011). In noisy areas, such as the Mediterranean Sea, the transmission may last 10 h or more.

Finally, the energy consumption due to the *Argos-2* operating mode can reach up to 30% of the energy budget during the Arvor's lifespan. Reducing this consumption would increase the life expectancy of the profiling float and thus reduce the cost of an Argo profile.

For all these reasons, the satellite communication system of the Arvor needed to take a great leap forward. Iridium has been used for a few years to fulfill these specific applications, but the use of the *Argos-3* system could be competitive if it allows a typical Argo profile or a high-resolution/multisensor profile to be transmitted in less than 15 min.

This paper describes the first long-term evaluation and implementation of the *Argos-3* interactive low- and high-data-rate communications on Argo profiling floats. Many prototypes have been deployed at sea, and their performances in terms of transmission are analyzed in this document. The results have been evaluated in comparison with the current *Argos-2* system and as an alternative to the Iridium system.

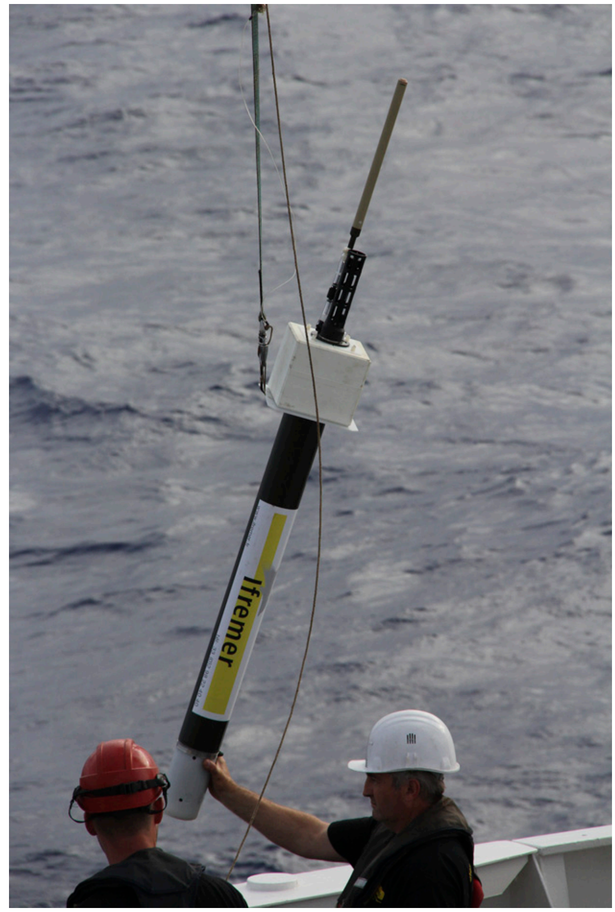

FIG. 2. Deployment of an Arvor *Argos-3* profiling float. The Arvor is 2.1 m high and the hull is 11 cm in diameter. The *Argos-3* antenna is on the upper end cap (in gray), near the CTD sensor. The ballast system that allows the float to move through the water column is on the bottom end cap. (Courtesy of Jérôme Blandin, Ifremer.)

2. Materials and methods

a. Arvor profiling float

The *Argos-3* satellite communication system has been evaluated in operational conditions on the Arvor profiling float, initially designed by Ifremer to meet the requirements of the Argo program. It is currently manufactured and commercialized by nke instrumentation.

The Arvor (Fig. 2) is 2.1 m high and weighs about 20 kg in air. Its upper end cap is fitted with a CTD sensor and a satellite communication antenna. The bottom end cap is fitted with a ballast system composed of an internal reservoir and an external ballast: transfers of oil from one compartment to the other changes the density

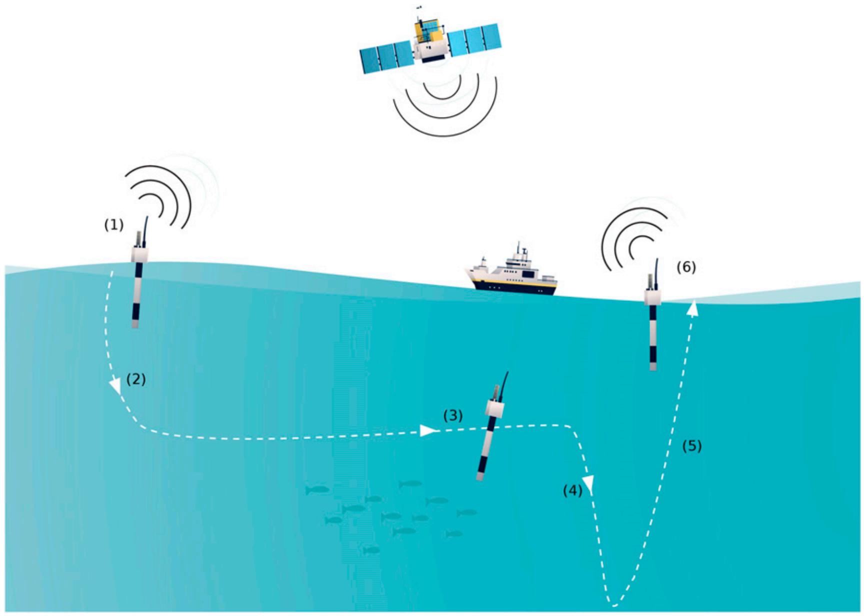

FIG. 3. Typical operational cycle of an Arvor. The float reduces its buoyancy (point 1), dives (point 2), and drifts at parking depth (point 3). It then travels to profile depth (point 4) and makes its measurement during the ascent (point 5). Transmissions and positioning are performed at the surface at the end of each cycle (point 6). (Courtesy of Euro-Argo Research Infrastructure.)

of the float (it changes its volume for a constant mass), inducing ascent or descent of the float in the water column (G. Loaec et al. 2004, meeting presentation). Electronic boards, batteries, and hydraulic components are integrated inside the hull.

A typical operational cycle of the Arvor is shown in Fig. 3 (Ollitrault and Rannou 2013). First, the float reduces its buoyancy (point 1) before diving (point 2) and stabilizes at its drifting depth (8–10 days at 1000 dbars; point 3). Then, the descent continues down to the profiling depth (maximum 2000 dbars; point 4). A profile is then recorded during the ascent to the surface (point 5). The float finally stays at the sea surface during the time it takes to transmit its technical and scientific data to a land-based station through a satellite communication system, and to be positioned (point 6) before starting a new cycle.

The float is positioned at the sea surface in order to locate the profile and to evaluate its drift. Floats fitted with *Argos-2* or *Argos-3* are automatically located (Lopez et al. 2014), with an accuracy of a few hundred meters (Costa et al. 2010), whereas Iridium requires an additional global positioning system (GPS), giving an accuracy of a few meters. This makes the integration of the antenna and increases the cost of the float more complex, but it is compulsory because of the poor accuracy of positioning estimations with Iridium, which has an accuracy of a few kilometers (Meldrum 2007).

b. Satellite communication systems

The Argos satellite communication system, created in 1978 thanks to French-American cooperation, was designed to collect scientific and oceanographic data and to improve safety at sea (Woodward et al. 2010). This system is operated by Collecte Localisation Satellites (CLS), a subsidiary of the CNES, Ifremer, and other French institutions.

Argos is a communication system based on polar-orbiting satellites covering the whole globe. Each satellite completes a full rotation of the earth in about 100 min (CLS 2014). As the number of satellites is limited, an Argos modem is only able to send data to a satellite after several minutes or several tens of minutes, depending on the constellation status. When a satellite receives data from an Argos modem, it is stored on board until a land-based station is in view. Then, the data are transmitted down to Earth, checked, and delivered to the end user (Fares 2011).

Until 2006, Argos only offered one transmission mode, *Argos-2*. A new series of satellites now completes the system, leading to a new generation of the system. *Argos-3* provides new functionalities (Ortega 2008; CLS 2011) but remains compatible with *Argos-2*. The main breakthrough is the addition of a downlink, which makes *Argos-3* a bidirectional system. The downlink is used to broadcast ephemerides to the modems (and their location to predict satellite passes), to secure transmissions thanks to a handshake protocol, and to

TABLE 1. Comparison of Argos and Iridium SBD communication modes; pseudoACK is the pseudoacknowledgment mode.

	Argos-2	*Argos-2* pseudoACK	*Argos-3* low-data-rate mode	*Argos-3* high-data- rate mode	Iridium SBD
Time needed to deliver data (from instrument to end user)	From a few minutes to a few hours				Near–real time
Downlink (possibility to send commands)	No	No	Yes	Yes	Yes
Acknowledgment	No	No	Yes	Yes	Yes
Frame size (bytes)	32	32	32	576	340
Uplink throughput (bits s^{-1})	400	400	400	4800	1000
Expected time to transmit an Argo profile	6–10 h	A few hours	<15 min	<15 min	<5 min
Need for satellite ephemeris calculations	No	Yes	Yes	Yes	No
Need for GPS	No	No	No	No	Yes

transmit commands toward the platforms. Specific *Argos-3* modems have been designed, called platform messaging transceivers (PMT).

In addition to the four *Argos-2* satellites, two *Argos-3* satellites were operational in 2014: *MetOp-A* since 2006 and *Satellite with Argos and Altika* (*SARAL*) since 2013. A satellite launch plan is scheduled until 2025, which ensures the continuity of the system.

On the other hand, Iridium is an American bidirectional communication system available since 1998. As Iridium consists of a constellation of 66 satellites (far more satellites than with the Argos system), an Iridium modem can connect to a satellite instantaneously from anywhere on Earth. Moreover, the satellites can communicate with each other, allowing data to be transmitted from the platform to the end user in near–real time. It offers many modes of communication, including the Short Burst Data (SBD) mode, which is comparable to *Argos-2* and *Argos-3*.

Five data communication modes are described hereafter and are compared in Table 1:

- the standard *Argos-2* mode [section 2b(1)]and the *Argos-2* pseudoacknowledgment mode [section 2b(2)], available on all *Argos-2* and *Argos-3* satellites;
- the *Argos-3* interactive low-data-rate mode [section 2b(3)] and the *Argos-3* high-data-rate mode [section 2b(4)], available on *Argos-3* satellites with an active downlink capability;
- the Iridium SBD mode (section 2b(5)].

1) ARGOS-2 COMMUNICATION MODE

Argos-2 is a unidirectional random access system: the only path of transmission is from the modem to the satellite (Fig. 4a). As no ephemerides are available in

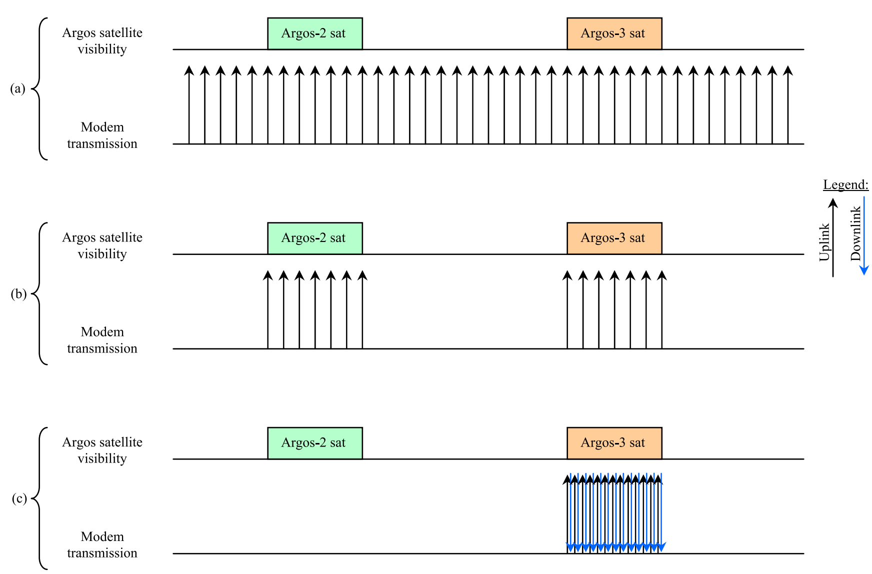

FIG. 4. Comparison of Argos mode protocols. (a) *Argos-2* mode consists of an uplink blind transmission, without knowing whether a satellite is visible. (b) *Argos-2* pseudoacknowledgment mode is an uplink blind transmission synchronized with satellite passes thanks to ephemerides embedded in the modem. (c) *Argos-3* interactive low-data-rate or high-data-rate modes are bidirectional, with satellite detection and an acknowledgment protocol.

this mode, *Argos-2* modems transmit data without knowing whether a satellite is in view for reception. Moreover, without any downlink, this mode cannot guarantee good-quality transmissions.

Argos-2 allows the Arvor profiling float to transmit its data in 32-byte frames every 40 s, with a throughput of 400 bits s^{-1}. Each frame is repeated randomly several times in order to increase the rate of error-free messages. The Arvor needs at least 6–8 h to transmit a typical profile of about 100 CTD points, that is, 500 bytes. This duration increases at low latitudes, as equatorial areas offer fewer satellite passes. Moreover, noisy areas, such as the Mediterranean Sea, need more repetitions of each frame to guarantee a good reception rate. As a result, the Arvor must transmit for at least 10 h at the surface.

2) Argos-2 pseudoacknowledgment mode

The *Argos-2* pseudoacknowledgment mode is the same as the standard *Argos-2* mode (messages of 32 bytes every 40 s), except that transmissions are synchronized with satellite passes, which can be predicted thanks to the ephemerides embedded in the PMTs (Figs. 4a and 4b). The advantage of this mode is that modems are turned off when no satellite is in view, thus saving energy.

There is no handshake protocol in this mode, as the downlink is not used. Consequently, any *Argos-2* or *Argos-3* satellite can be addressed. However, the modem has to be in regular view of *Argos-3* satellites to recover the broadcasts of ephemeris updates for calculation of satellite pass predictions and to recover its location. If this is not the case, then the modem is forced into a special "backup" mode for a few hours at the surface, where it will be updated.

3) Argos-3 interactive low-data-rate mode

The *Argos-3* interactive low-data-rate mode is only available on the new generation of satellites, which offer a downlink (Fig. 4c). The frame size and the throughput remain the same as for *Argos-2* (32 bytes at 400 bits s^{-1}), but the transmission rate is not limited to 40 s and can be as low as 5 s if no errors occur.

In this mode, the system acknowledges the frames when they are correctly received aboard satellites, which guarantees good transmission. Moreover, the end user can send commands to the distant equipment and change its configuration. The ephemerides are used to synchronize transmissions with satellite passes.

4) Argos-3 high-data-rate mode

The *Argos*-3 high-data-rate mode offers the same functionalities as the interactive low-data-rate mode (Fig. 4c). However, it uses a specific frequency band and modulation, allowing the transmission of 576 bytes per frame (18 times more than in the interactive low-data-rate mode) and a data rate of 4800 bits s^{-1} (12 times more than the interactive low-data-rate mode).

5) Iridium SBD mode

SBD mode is a bidirectional communication system. It offers a near-real-time and handshake transmission to send uplink frames of 340 bytes and downlink frames of 270 bytes at a throughput of 1000 bits s^{-1}. The transmission rate is not limited and equivalent to *Argos-3* in practice (one message every few seconds). It has been used on the Arvor/Provor family for a few years and allows the transmission of an Argo profile in less than 5 min, including the time needed to determine the location of the float with the embedded GPS.

Another Iridium mode, named Rudics, is also implemented on profiling floats to transmit a huge amount of data, but it is not comparable with *Argos-3*.

c. *Test bench*

The *Argos-3* system was evaluated on a test bench in our laboratory before being tested on the Arvor float at sea, in order to validate the low-level software libraries used to implement the *Argos-3* protocol and to qualify the high-level software in simulated operational conditions.

An Arvor float is composed of the following active subassemblies (Fig. 5, left):

- a main electronic board that controls the Arvor;
- a satellite communication modem and its antenna;
- hydraulic circuitry that controls the buoyancy of the float and manages its movements through the water column;
- one or many sensors.

Our bench reproduces the behavior of an Arvor in its environment, as if it were in operation at sea. It is composed of (Fig. 5, right) the following subassemblies:

- the main electronic board of an Arvor;
- an *Argos-3* modem and its antenna;
- a computer and a man-machine interface (MMI) that 1) monitors the hydraulic commands of the electronic board, 2) simulates the float's buoyancy and its movement through the water column, and 3) emulates the sensors and provides datasets to the electronic board.

d. *MMI for* Argos-3 *protocol analysis*

The communication protocol between the modems and the satellites in the *Argos-3* modes is far more

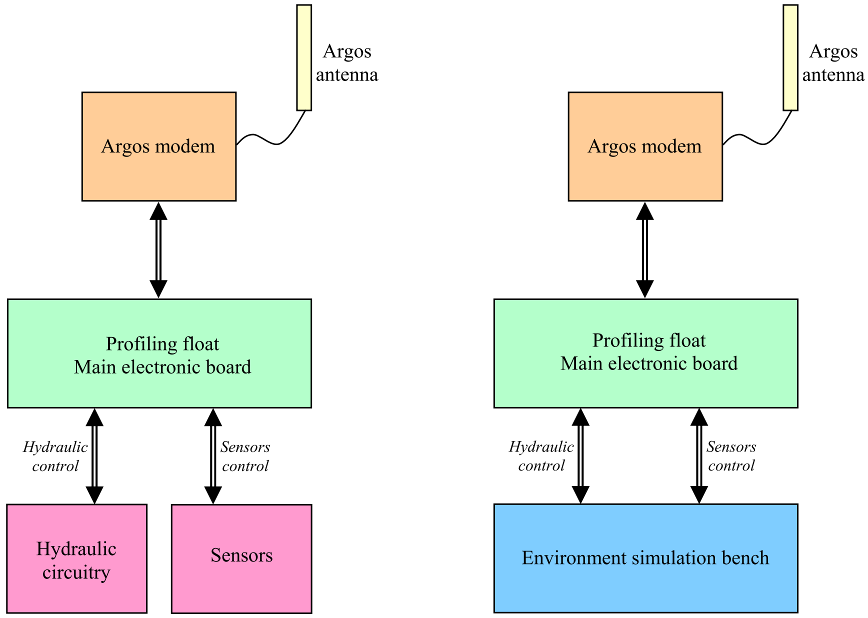

FIG. 5. (left) The Arvor is composed of a main electronic board that controls the float: satellite communications, hydraulic circuitry to manage movements through the water column, sensors. (right) Our test bench is based on the same electronic board and communication system; the hydraulic circuitry and the sensors are emulated to reproduce environmental conditions, allowing the qualification of our software as if it were in operation at sea.

complex than with *Argos-2*. To analyze this protocol, a specific MMI was developed, which can be used in the following two configurations:

- It can monitor the data flow between the modem and the electronic board of the Arvor in real time. This is done by logging and analyzing all serial link dialogues, thus restricting this procedure to laboratory tests, using our test bench.
- It can analyze exchanges between the modems and the satellites. This cannot be done in real time, as it requires specific technical files, related to all receptions and transmissions on the satellite, provided for the purpose of our study by CLS. This configuration was used to analyze the results obtained for operations at sea.

Each analysis provides the characteristics of the satellite pass (retrieved from the CLS website) and identifies all exchanges in both directions. Thus, it is known when the modem tries to open a communication session, when a message is transmitted, and whether it is acknowledged by the satellite, etc.

The main part of the MMI is shown in Fig. 6. It represents an *Argos-3* pass and the modem–satellite exchanges, according to time and azimuth. Each arrow represents a different message in the *Argos-3* communication protocol. The symbols used to represent these exchanges are as follows:

- solid blue arrow: the modem requires a new session;
- dashed blue arrow: the modem requires a new session, but the demand is received on board the satellite with bit errors;
- solid green arrow: data frame transmitted successfully (received on board the satellite without errors and its acknowledgment is received in return by the modem as well);

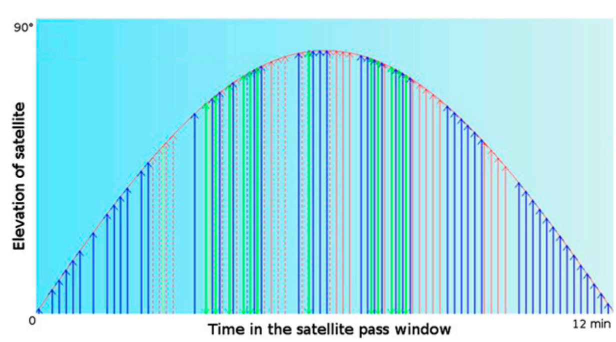

FIG. 6. MMI for *Argos-3* protocol analysis: each arrow represents a different message in the *Argos-3* modem–satellite communication protocol (from the satellite's point of view). Blue arrows are session opening requests (solid: no error, dashed: bit errors), solid green arrows are messages successfully transmitted and acknowledged, red arrows are messages unsuccessfully transmitted (solid: downward acknowledgment not received, dashed: uplink bit errors).

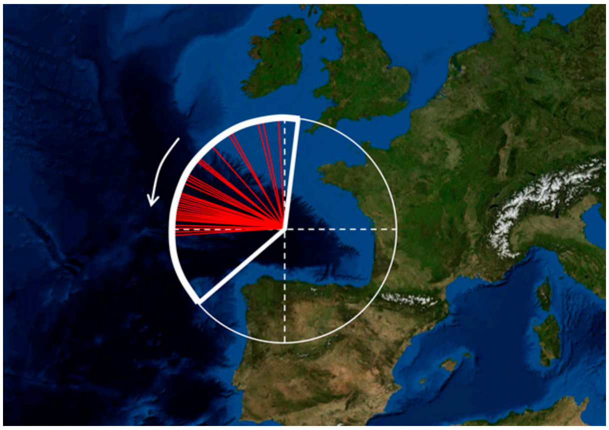

FIG. 7. MMI for *Argos-3* azimuth performance analysis. Our MMI shows the azimuth where the transmissions are concentrated during a satellite pass.

- solid red arrow: data frame transmitted by the modem and received on board the satellite without errors, but its downward acknowledgment is not received by the modem;
- dashed red arrow: data frame transmitted by the modem and received on board the satellite with bit errors.

The MMI also represents the spatial pass of the satellite over the modem location (Fig. 7). It can be used to analyze the quality performances of the communication versus the azimuth of the satellite during a pass.

Finally, the MMI also provides transmission statistics related to the efficiency of the transmissions.

3. Results and discussion

This chapter is divided into three separate sections:

- first, we present the results of the *Argos-3* interactive low-data-rate mode;
- then, as our work led to the design of a new and more robust mode, named the *Argos-3* interactive low-data-rate *full-acknowledgment* mode, we detail its results in the laboratory and at sea;
- finally, we describe our work on the *Argos-3* high-data-rate mode.

a. *First Argos-3 interactive low-data-rate mode*

The objective of the *Argos-3* interactive low-data-rate mode is to transmit a typical Argo profile in a few minutes, in order to be competitive with Iridium SBD and to improve on the *Argos-2* communications, which required 8–10 h.

1) Preliminary work and algorithm

While implementing the first *Argos-3* interactive low-data-rate mode, we quickly noticed that the modem designed by Kenwood was not exploiting the full capabilities of the *Argos-3* system, due to a lack in its design. In particular, the modem did not really offer a full guarantee of good-quality transmissions, as expected according to its specifications, which is important when compared to Iridium. In fact, once all data frames have been loaded into the modem and transmitted, they are automatically erased one by one if one of the following conditions is fulfilled:

- the acknowledgment is received back by the modem, meaning that the data frame was correctly transmitted;
- or after N successive transmission attempts, every interactive repetition period (IRP) seconds ($N \leq 5$, IRP = 10 s by default), even if acknowledgment is not received.

This means that a data frame can be erased from the internal buffer of the modem without ensuring that it was correctly received by the satellite.

To get around this problem, we had to control the way the modem works and particularly the way it deletes data. We used the following algorithm:

1) one (and only one) data frame is downloaded to the modem;
2) then, we waited for the data frame to be automatically deleted from the modem:
   2a) if the data frame was deleted before N*IRP = 50 s, then the transmission was successful;
   2b) if the data frame was deleted after N*IRP = 50 s, then it had been erased without knowing whether it was received by the satellite. In this case, the data frame was reloaded and the same operation started again.

Developing a way around this issue has made our software more complex, as we had to be in complete charge of transmission acknowledgment, instead of the modem.

2) Laboratory tests

During our evaluation of the first *Argos-3* interactive low-data-rate mode, and thanks to our dedicated MMI, we focused on six main types of exchanges between the modem and the satellite, listed below:

- session requests (uplink) in order to start a new transmission session;
- go-ahead messages when a session is granted (downlink);
- data transmissions (uplink);
- acknowledgments of data messages (downlink);
- commands to be transmitted to the distant platform (downlink);
- housekeeping messages to improve the location of the platform by the modem (uplink).

In the first *Argos-3* interactive low-data-rate mode, the PMT sends a request to the satellite for a new

TABLE 2. Time needed to transmit an Argo profile (on average) with the first *Argos-3* interactive low-data-rate mode. The results at sea were not satisfactory, due to a defect in the design of the modem and sensitivity to noise. The modem was redesigned, leading to the full-acknowledgment mode.

	Time needed to transmit an Argo profile (on average)
Argos-2	8–10 h
Iridium	A few minutes
First *Argos-3* interactive low-data-rate mode in laboratory	One satellite pass (<12 min)
First *Argos-3* interactive low-data-rate mode in the Mediterranean Sea	A few hours on average

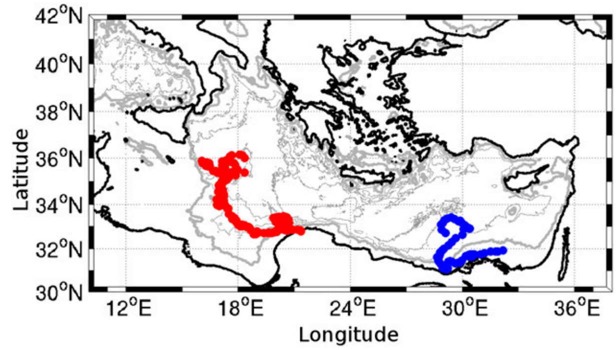

FIG. 8. First deployments of Arvor floats fitted with *Argos-3* in the Mediterranean Sea.

session, during which data are loaded into its internal buffer. In standard use, all messages are loaded at the same time; as a result there is only one session request at the beginning of the communication. As explained before, we had to implement a workaround solution, which consists of loading messages one by one in order to secure transmissions because of a defect in the modem design. The consequence that we observed during our laboratory tests was that the modem requests a new session with each new message, which considerably slows down the transmission performances.

Laboratory tests on our bench showed that the following objective can be achieved: the transmission of an Argo profile during a satellite pass of less than 12 min is possible (Table 2). We successfully transmitted an average of 130 CTD samples per satellite pass (650 bytes), which is better than our objective of an Argo profile of 100 samples.

3) SEA TRIALS

Two Arvor profiling floats were fitted with this mode of transmission and deployed in the Mediterranean Sea on 20 and 23 February 2011 (Fig. 8). They performed 86 and 233 cycles, respectively, but as they came closer to the shores after a few months, some profiles were recorded in shallow waters, thus reducing the number of CTD samples to be transmitted.

Because of the lack of full acknowledgment offered by the modem, the *Argos-3* capabilities were not fully exploited at sea. Consequently, our objective was not met for these two profiling floats: a complete profile could not be transmitted in only one *Argos-3* satellite pass—that is, in less than 15 min—except on very few cycles (Table 2). Instead, a few hours at the sea surface were needed for transmissions.

Our MMI was used to analyze transmissions during this test at sea and to understand why the results were disappointing. As expected, many session opening requests were sent by the modem to the satellite due to our work-around algorithm. However, we also noticed that the downlink, used to send acknowledgments, was very noisy in the Mediterranean Sea. This could be determined by two observations: 1) many session opening requests had to be repeated, meaning that the go-ahead message that grants the session was not received back by the modem; and 2) many messages were received correctly by the satellite but repeated by the modem, meaning again that the downward acknowledgment was not received. Difficulties due to continental noise had already been encountered with the standard *Argos-2* transmissions in this region, but we found that this noise also has an impact on *Argos-3* low-data-rate transmissions.

4) CONCLUSIONS

The problem of noise could not be solved in a simple way. It would have required modifying the frequencies and modulations used by the *Argos-3* system.

The fact that one session opening request is sent for each message is due to our turnaround algorithm and not to the *Argos-3* specifications that only require one session opening request at the beginning of each satellite pass. These redundant requests waste half of the air time. To fully exploit the capabilities of the *Argos-3* system and to improve our results while maintaining the same level of requirements, we thus needed to reduce the number of session opening requests down to only one at the beginning of a satellite pass. Consequently, the internal algorithm of the PMT had to be modified, so as to erase a message from the internal buffer under only one condition: if and only if the acknowledgment was received by the modem. In this way, all messages can be loaded by the modem before the beginning of transmission, and only one session opening request will be sent. This should save approximately 50% of air time.

Therefore, we asked Kenwood, the manufacturer of the PMT, to modify its algorithm. This has led to a new mode, compliant with the *Argos-3* system specifications: the *Argos-3* interactive low-data-rate full-acknowledgment mode, described in the following section.

b. Argos-3 *interactive low-data-rate full-acknowledgment mode*

1) Preliminary work

Our initial work, described in the previous section, led to the design of this new mode. Kenwood modified the internal algorithm of the modems, leading to a new generation of PMT. The condition that deletes the messages after N successive attempts has been removed, so as to erase messages from the internal buffer of the modem only if the downward acknowledgment from the satellite is received. Our algorithm was modified to load the entire dataset of a profile to the modem in one go, which means that only one session opening request from the modem should be necessary.

2) Laboratory tests

The tests were conducted in the laboratory on our test bench, over a period of a few weeks. We confirmed that the time required to transmit a typical Argo cycle was halved with this new mode as expected, showing that 50% of air time was saved when session opening requests are not sent before each data frame. The full-acknowledgment protocol was then validated, saving considerable time and improving the transmission performances.

TABLE 3. Time needed to transmit an Argo profile (on average) with the *Argos-3* interactive low-data-rate full-acknowledgment mode.

	No. of cycles	Time needed to transmit an Argo profile (on average)
Atlantic	171	6 min 20 s
Mediterranean Sea	54	3 min 10 s

3) Sea trials

This mode was implemented on two Arvor profiling floats, described as follows:

- the first one was deployed in the Bay of Biscay (North Atlantic Ocean) on 21 October 2012;
- the second one was deployed in the Mediterranean Sea near Majorca on 25 May 2014.

The results, summarized in Table 3, were highly satisfactory. Figures 9 and 10 show the time needed to transmit an Argo profile after each cycle. The Arvor deployed in the Atlantic performed 171 cycles and needed an average of 6 min, 20 s to transmit its profile, while the Arvor deployed near Majorca (54 cycles) needed an average of 3 min, 10 s. Yet, the Mediterranean Sea is known to be affected by electromagnetic continental noise (Gros et al. 2006), as noted in the previous section. It is worth noting that the

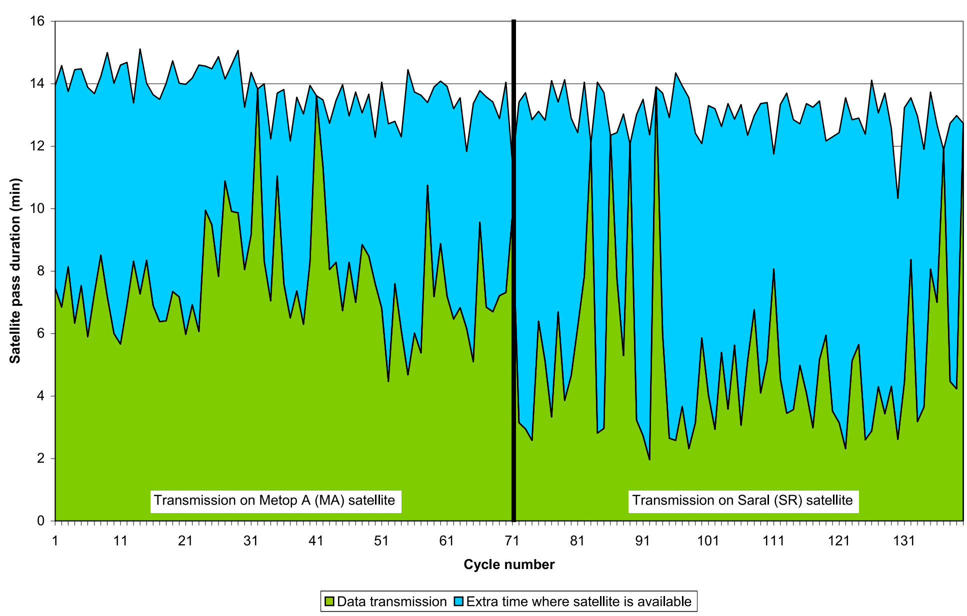

FIG. 9. Performance of transmissions on the Arvor *Argos-3* in interactive low-data-rate full-acknowledgment mode, Bay of Biscay. Time needed to transmit an Argo profile (green) and extra time that could have been used to transmit more data (blue) vs the number of cycles of the Arvor. Performances have improved since the launch of *SARAL*, with which this float synchronized.

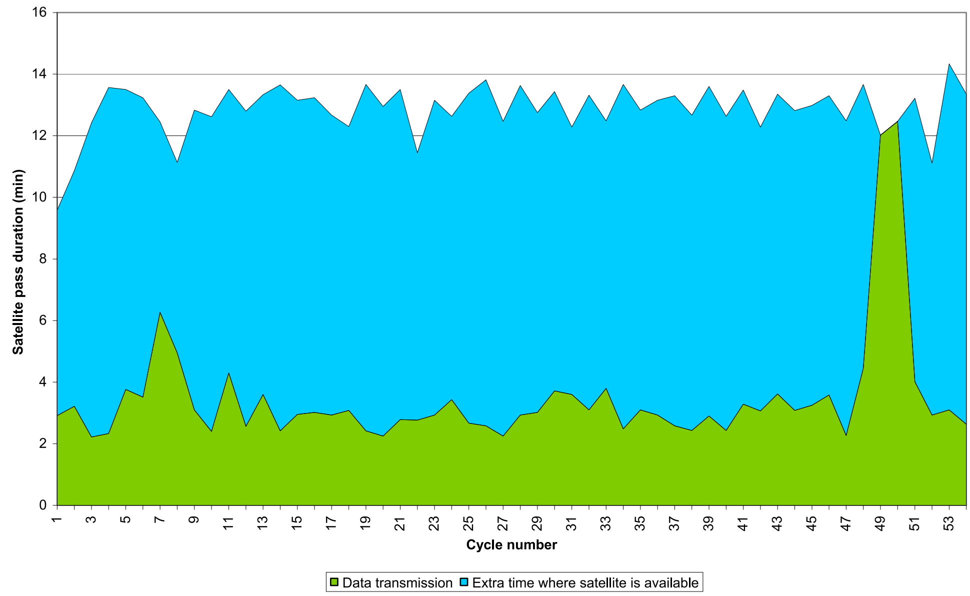

FIG. 10. Performance of transmissions on the Arvor *Argos-3* in interactive low-data-rate full-acknowledgment mode, Mediterranean Sea. Time needed to transmit an Argo profile (green) and extra time that could have been used to transmit more data (blue) vs the number of cycles of the Arvor

performances have improved since *SARAL* became operational (May 2013). This can be explained by a better signal-to-noise ratio on *SARAL* and a difference in noise levels affecting the transmissions (because *SARAL* passes over Europe earlier in the morning than the *MetOp-A* satellite, the data exchanges are less impacted by industrial noise). Furthermore, a reduction in noise has been observed over the past years.

A detailed analysis of the communication performances was carried out on the profiling float deployed in the Atlantic. During this test, the entire dataset could be transmitted in one go during 94% of the *Argos-3* optimal satellite passes. The other 6% had to continue the transmission onto the following satellite passes, thus increasing the time spent at the surface from a few minutes to a few hours, depending on the satellite constellation status. The analysis showed that the performances were much better during western passes (over the Atlantic Ocean) than during eastern passes (over Europe). This was due to the continental noise that affected the exchanges between the modem and the satellites: messages were received by the satellite with errors. One solution would have been to exploit only western passes, but the PMT does not give any indication of the azimuth of the satellite passes in its ephemerides. This could have been a solution to improve the results, but it would have been complicated from an operational point of view, as the best azimuth depends on the deployment zone (western passes are better in the Bay of Biscay but eastern passes are better in the northwest Pacific Ocean).

Furthermore, the tests showed that the energy budget needed to transmit an Argo profile in the *Argos-3* full-acknowledgment mode is 5 times less than in the *Argos-2* mode. The lifetime of the float is thus increased from 250 cycles to more than 300 cycles.

4) CONCLUSIONS

The results are highly satisfactory in this mode: two Arvor floats, using the *Argos-3* interactive low-data-rate full-acknowledgment mode, showed very good transmission performances at sea, even in the Mediterranean Sea, an area known to be challenging regarding Argos communications. A standard Argo profile, composed of 100 CTD samples (500 bytes), is transmitted in a few minutes, whereas 6–10 h were needed using the *Argos-2* generation system.

c. Argos-3 *high-data-rate mode*

The objective of the *Argos-3* high-data-rate mode is to transmit a substantial quantity of data during only one satellite pass: either high-resolution profiles (1000 CTD samples instead of 100, i.e., 5 kbytes) or data from profiling floats equipped with additional sensors.

For compatibility reasons, a high-data-rate frame is the concatenation of 18 low-data-rate frames. This simplifies the design and the coding of this transmission

TABLE 4. Quantity of data (kbytes) sent during a satellite pass with the *Argos-3* high-data-rate mode vs azimuth and location of the test. This experiment showed high sensitivity of the high-data-rate mode to noise.

	Eastern passes	Western passes
Performance in Brest and Hennebont (France)	1.25	15–20
Performance in Réunion (Indian Ocean)	20	20

mode, as many low-level functions are identical. High-level routines are the same in both modes, only the configuration of the modem changes.

1) LABORATORY TESTS

To study the high-data-rate mode performances and limitations, our test bench was configured to send a huge amount of data. After each *Argos-3* satellite pass, we calculated the amount of data transmitted, in order to update our statistics. In this mode, only satellite passes of more than 10 min were exploited.

We immediately noticed that in Brest and Hennebont (France), over a period of a few weeks, the performances were extremely different, depending on whether the satellite passed west or east of our location (Table 4). Almost all western passages allowed our bench to transmit 3000–4000 CTD samples per pass (15–20 kbytes), which is the excellent result that we expected. However, eastern passages never allowed more than 2500 CTD samples (12.5 kbytes) to be transmitted, and the performances were very heterogeneous: on average, only 250 samples could be sent (1.25 kbytes), and sometimes none. Consequently, we hypothesized that eastern transmissions could be affected by European continental noise.

To confirm this, the same protocol was conducted over 2 weeks from the CLS local office of Saint-Pierre (Réunion, Indian Ocean), an area not affected by environmental electromagnetic noise. The results were excellent, whatever the azimuth of the satellite. Almost 4000 CTD points (20 kbytes) were transmitted during each pass (Table 4).

Thus, it appears that the *Argos-3* high-data-rate results are only satisfactory when the satellite is not subject to noise, which is the main problem above Europe (Gros et al. 2006). Disturbance due to noise is well known for *Argos-2* in some regions, like the Mediterranean Sea and Asia, but as for the interactive low-data-rate mode, it is the first time that it is shown for the *Argos-3* high-data-rate mode.

2) SEA TRIALS

While the laboratory evaluations were in progress, the high-data-rate mode was integrated on the Arvor float, due to the project calendar and at-sea scheduling issues. Despite the disappointing results in Europe, we decided to run at-sea experiments by deploying the Arvor floats in ''noise free'' conditions, thanks to an opportunity cruise in the middle of the Atlantic Ocean.

Two Arvor floats fitted with *Argos-3* high-data-rate transmissions were deployed at sea, in August 2013 (Fig. 2), south of the Azores (North Atlantic Ocean).

Unfortunately, the embedded software on both Arvor floats encountered problems during these trials, which were not managed correctly. The technical messages sent via Argos allowed an a posteriori analysis, which proved that something unexpected had happened while reading the satellite pass predictions from the PMT. One float performed only one cycle, while the other performed four cycles, before being lost due to this undetermined problem.

To understand the origin of this unexpected behavior, many tests were conducted: the Arvor algorithm was requalified on our test bench, transmissions were conducted with an Arvor float for many weeks in order to verify whether the bug was related to an integration problem, and simulations were run by CLS with the ephemerides algorithm embedded in the PMT. None of these tests was successful.

3) CONCLUSIONS

As this operation at sea was the last one planned, experimentation on the high-data-rate mode was stopped. No further work was devoted to understanding and solving the problems that occurred at sea using the *Argos-3* high-data-rate mode, or to determining whether they were related to an Arvor software bug or to a modem issue.

Anyway, the fact that the *Argos-3* high-data-rate mode was affected by noise showed that the prospects for using it in operations were not satisfactory for our application.

d. Miscellaneous

1) SELECTION OF OPTIMAL SATELLITE PASSES

Depending on the configuration of the satellite constellation, a modem can see a satellite at different angles and for durations ranging from a few seconds to 15 min. Our application will only select satellite passes that allow the transmission of sufficient messages. Some tests have been carried out to determine the characteristics of these ''optimal'' passes: a maximum elevation greater than 30° and for a duration of at least 10 min.

At sea, the Arvor synchronizes its profiles with optimal satellite passes only, arriving at the surface just before the pass.

Furthermore, the objective is to transmit the data acquired by the Arvor profiling float during a single optimal satellite pass. If this is not possible, then the transmission continues in *Argos-2* pseudoacknowledgment mode.

2) Ephemerides

We noticed that the modem did not provide any ephemerides when a satellite pass was in progress, as it dedicated all its resources to communications, even if it was an *Argos-2* pass. As a result, as two or three satellites can overlap for up to 40 min, no ephemerides could be read during this period.

As we needed to obtain ephemeris predictions before the beginning of the transmissions in order to transmit the date and time of the next profile, the profiling float had to arrive at the surface 40 min before the optimal pass. This was done in the first interactive low-data-rate mode evaluation.

A work-around algorithm was then implemented in order for the float to arrive at the surface just a few minutes before the optimal pass. The algorithm activates each satellite in the modem configuration, one by one, while deactivating the others. If the considered satellite is in the process of passing, it is ignored. Otherwise, the float stores the next optimal pass for this satellite. This operation is repeated for all available satellites. Finally, the float is allocated the very first optimal pass. This method saves at least half an hour, thus reducing the time spent at the surface, which is critical as explained previously.

Moreover, we had to secure our software when retrieving ephemerides from the modem. Sometimes, the modem gave optimal passes that had already ended, or in very particular test conditions, it returned passes with erroneous characteristics (duration of 80 min, e.g, which is impossible, as a satellite almost completes a full rotation of the earth in that period of time).

All these workaround solutions have greatly complexified our software, but they were necessary to optimize the implementation of *Argos-3* on the Arvor.

4. Conclusions and outlook

The Arvor oceanographic profiling floats are used to monitor the global ocean. They currently need to transmit more data (high-resolution or multisensor profiles) in only a few minutes, in order to reduce the time spent at the surface. Thus far, because of these requirements, the floats have been fitted with Iridium, as *Argos-2* was not suitable. Following the arrival of the new-generation Argos, named *Argos-3*, we decided to evaluate and implement it on Arvor floats.

The "*Argos-3* high-data-rate mode" aims to transmit a significant quantity of data. Many tests were performed, confirming that this mode is considerably impacted by continental electromagnetic noise. Transmissions are almost impossible when a satellite passes over Europe. Nevertheless, two floats were deployed in the North Atlantic, but they encountered problems due to a software or modem problem. Thus, implementation of the *Argos-3* high-data-rate mode on the Arvor was abandoned. However, continental noise in the bandwidth used by the Argos system has been slowly decreasing over the last few years, thanks to the trend in communication systems (i.e., radio communication equipment) to shift up to higher-frequency bands.

The "*Argos-3* interactive low-data-rate full acknowledgment mode" was evaluated at sea: one float was deployed in the North Atlantic and a second one in the Mediterranean Sea near Majorca. They both gave excellent results: thanks to *Argos-3*, a typical Argo profile—that is to say 100 CTD samples (500 bytes)—can be transmitted in less than 6 min. This is a considerable improvement compared to the average 8–10 h necessary with *Argos-2*, and it is similar to the Iridium Short Burst Data (SBD) transmissions, which require about 2 min on average.

In conclusion, we can say that this evaluation was difficult, because we were one of the first users to embed *Argos-3* and to test its limitations in an application where there were multiple constraints. We pointed out for the first time that the *Argos-3* system was sensitive to electromagnetic noise and particularly in the high-data-rate mode, which cannot be used satisfactorily in applications with strong constraints in some parts of the globe. Our work has led to a new and more secure implementation of the interactive low-data-rate mode in the modem, called full acknowledgment, which gave excellent results at sea. This mode appears as a great opportunity in many marine applications to retrieve remote scientific data.

To evaluate the stability of the results at sea and to determine whether the Arvor *Argos-3* could be industrialized, one more prototype was deployed in the Mediterranean Sea in June 2015, and three more prototypes will be deployed in the South Atlantic Ocean and the Indian Ocean in August 2015.

In our application, the cost of Iridium and *Argos-3* is similar, taking into account the hardware and the transmissions charges. For the Argo core mission (profiling floats fitted with only a CTD and acquiring low-resolution profiles), the *Argos-3* interactive low-data-rate full-acknowledgment mode offers the same functionalities as Iridium: the transmission of a standard CTD profile in a few minutes and the possibility of sending remote commands to the equipment at sea. Moreover, CLS (provider of *Argos-3*) offers value-added services like data storage, data decoding, and quality control, while Iridium SBD only provides raw data via e-mail. However, *Argos-3* is not currently capable of fulfilling the need to transmit more data (high-resolution profiles or multisensors profiles), whereas Iridium has been used over the past few years for these applications.

A new generation of Argos, Argos-4, is already on the way. Argos-4 will solve the problems encountered during our evaluation. The frequency bandwidth of the downlink, which is also affected by noise, has been expanded to be more robust. The noise margin of the high-data-rate mode has been reevaluated, so as to be less affected by continental noise.

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