NX-2G : autonomous BBOBS-NX for a highly mobile broadband seismic and tilt observation at the seafloor

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***Abstract*—Developments of the broadband ocean bottom seismometer (BBOBS) and its new generation system (BBOBS-NX) have been a base to establish the ocean floor broadband seismology, since 1999. Our BBOBS and BBOBS-NX data is adequate for modern broadband seismic analyses to study the deep Earth interior. Especially, the BBOBS-NX can offer the low noise horizontal data comparable to land seismic stations in periods longer than 10 s. As a variation of the BBOBS-NX, the BBOBST-NX has been developed too, which enables the additional tilt measurement at the seafloor with the broadband seismic data. Their high performance can be a breakthrough to realize the geodetic observation network at the seafloor for slow slip event observations for example. A defect of the current BBOBS-NX system is necessity of the submersible vehicle in its operation of the deployment and the recovery. This condition limits possibilities of observations, compared to observations by the BBOBS that can be operated even on a small fishery boat. The development of the autonomous BBOBS-NX, NX-2G, is really required to elucidate the Earth interior below wide oceanic area in the future.**

Keywords—ocean bottom seismometer; broadband seismology; tilt-meter; autonomous system; seafloor observation

I. INTRODUCTION

To understand the Earth internal structure and geodynamics, seismic observations in the oceanic area, which covers 2/3 of the Earth surface, should play important role. But, except some oceanic islands, such observatories are very sparse because of technical difficulties to construct and maintain them. From this point of view, temporal seismic observations have been conducted by using ocean bottom seismometers (OBS) [1]. Because the modern seismology has been improved with land broadband seismic observations, it is required to obtain the similar seismic data at the seafloor. So, we had developed the broadband OBS (BBOBS) and its new generation system (BBOBS-NX [2], Fig. 1), and, with them, several practical observations have been performed to create a new category of the ocean floor broadband seismology, since 1999. Now, our BBOBS and BBOBS-NX data is proven to be at acceptable level for broadband seismic analyses [3]. Especially, the BBOBS-NX is able to obtain the low noise horizontal data comparable to the land station in periods longer than 10 s (Fig. 2), which is good for modern analyses of the mantle structure. In these studies, the period range mostly used is about 10–200 s, but in further longer period range has been unknown region in the seafloor observation. Our BBOBS and BBOBS-NX can be a breakthrough to realize the geodetic observation network at the seafloor.

Two kinds of attempts to expand observation range toward the geodetic one have been started since 2009, based on our BBOBS technology. One is for detecting vertical displacement by attaching an absolute pressure gauge (APG) in the BBOBS system. The highly stable frequency oscillator within the OBS recorder is adequate for precise pressure measurement of the APG. This BBOBS+APG system has been operated since 2009 [4]. Another is the tilt observation just beneath the seafloor by using the BBOBS-NX system, the BBOBST-NX. The tilt is measured by using mass position signals of two horizontal components of the broadband sensor, which is equivalent to the CMG-3T (360 s, Guralp systems). The tilt observation at the seafloor has been believed difficult because the instrument is installed on the soft sediment, so that some tilt measurements have been planned in the borehole by the deep-sea drilling. From some test observations of the BBOBST-NX, we found that it has tilt resolution of less than 1 μ radian.

Both of the BBOBS-NX and the BBOBST-NX are useful in present, but the final goal of these developments is to make them as the autonomous system, like as the BBOBS. Then, we can perform broadband seismic and tilt observations without the submersible vehicle, which leads us more opportunities and spatially dense observations. In this paper, we show the present plan of the autonomous BBOBS-NX system (hereafter, NX-2G) with our preparations to realize this new system.

II. CURRENT SYSTEMS

A. BBOBS

The BBOBS had been developed in 1999 based on the short-term OBS with geophones using the glass sphere housing [1]. This type of OBS is an autonomous system, because of the freefall deployment and the self pop-up recovery by its

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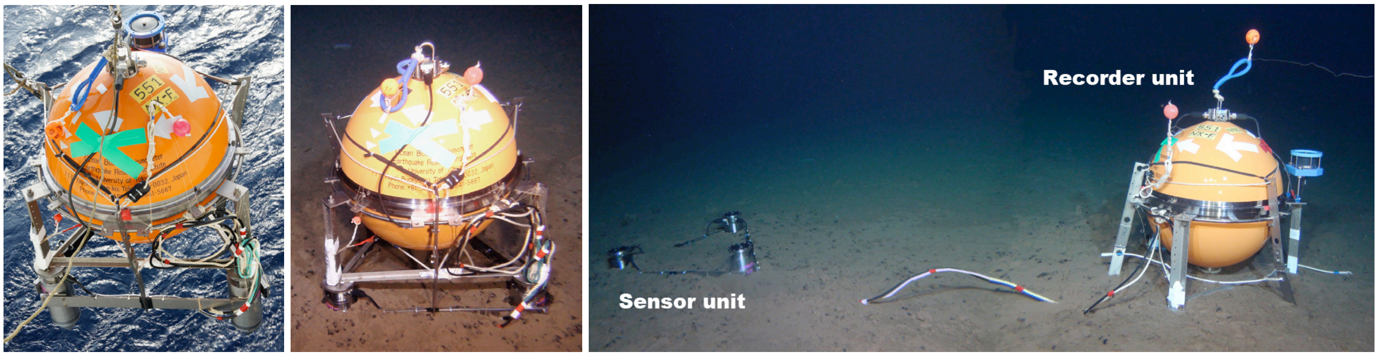


Fig. 1. The BBOBS-NX, soon before the free-fall deployment from the sea surface (left), after the landing with enough penetration of the sensor unit into the sediment (center), and in the observation after the operation by the remotely operated submersible vehicle (ROV) (right). The sensor unit and the recorder unit are temporally connected during the deployment until the landing with descending speed of about 80 m per minute. Because the part of the sensor unit exposed in the sea water is small amount as seen in the right photo, it reduces the noise level due to the bottom current. The recovery is also performed by the ROV.

buoyancy. The housing of the BBOBS is a titanium sphere of 650 mm in diameter with more than 75 kgw of buoyancy. The broadband sensor is the CMG-3T that is almost same as used at land seismic stations. This sensor is installed on the active leveling unit to correct the tilt after landing of the BBOBS on the seafloor, which can keep level under tilt up to ±20°. Now, we use the third generation OBS data recorder of low power consumption (~200 mW) operated with 24 bit, 6 channels, and 100 Hz sampling rate. By using 60 DD size lithium cells, the observation period can be about 400 days. This type of the BBOBS has been deployed more than 130 times, and the recovery rate is above 95 %.

The noise model [5] of the BBOBS (Fig. 2) usually shows that the noise level of the vertical component is between the new high noise model (NHNM) and the new low noise model (NLNM) [6] in longer periods more than 20 s, which indicates the data is comparable to that obtained at land seismic stations. But, the noise level of horizontal components lies above the NHNM, and the variation in time is larger than the vertical component one. We could perform some amount of modern analyses with this BBOBS data, but the reduction of the noise level of horizontal components was heavily required to achieve maximum results from the limited data of temporal OBS observations.

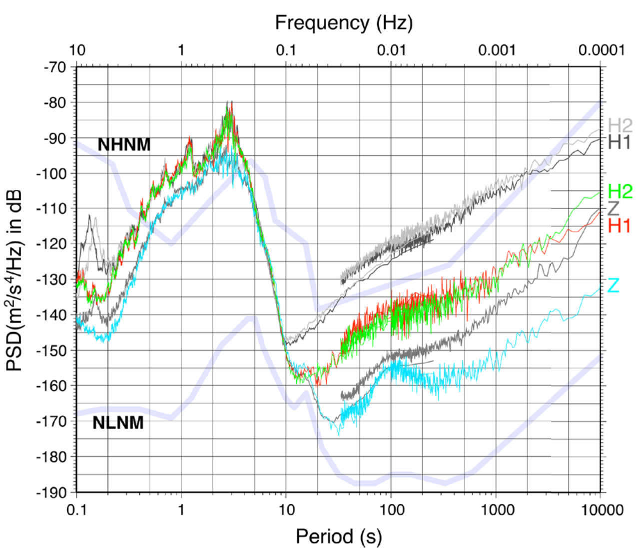


Fig. 2. The noise model of the BBOBS-NX (color) and the BBOBS (grayscale) at the site (4900 m depth) in the Philippine Sea. The NHNM and NLNM are also indicated. In the vertical component (Z), difference of noise levels between two types of OBS is small except in periods more than 200 s. But, large noise reduction of about 20 dB is achieved in horizontal components (H1 and H2) in longer than 20 s period.

B. *BBOBS-NX*

The noise reduction of horizontal components is the main aim of the BBOBS-NX. It had been demonstrated that the buried sensor package could achieve excellent result [7], but the system was large and heavy. So, we originally designed the sensor unit with smaller diameter and low profile pressure cases for each component to enable enough penetration into the sediment by the free-fall deployment (Fig. 1). The broadband sensor is specially developed for this system, which can operate up to tilt of ±8°, because no leveling mechanism is used to minimize the height of the pressure case. By attaching the electric compass with the tilt-meter, the data of the vertical component is post-processed to eliminate the contamination of signals of horizontal components. Other specifications are same as those of the BBOBS except about the self pop-up recovery function.

The first BBOBS-NX of this design was deployed in June 2009 and recovered in Dec. 2009. Fig. 2 shows the noise model of the BBOBS-NX and the BBOBS to compare the reduction of noise. The change in the vertical component is small, but the noise level of horizontal components became lower than before about 20 dB. It provides us advantage in number of seismic events that adequate for modern analyses as more than 10 times because of the Gutenberg-Richter law, that generally indicates 10 times more events in 1.0 smaller magnitude. Practical observations with several BBOBS-NXs have been conducted already since 2010. This new system brought large attention in the international OBS community at the workshop in 2013 [8].

C. *BBOBST-NX*

For the study of successive processes in the earthquake occurrence, the slow slip event (SSE) at the plate boundary becomes a target because of its slow propagation speed and almost steady and short interval. As most of such boundary is below the seafloor, geodetic observations there are required

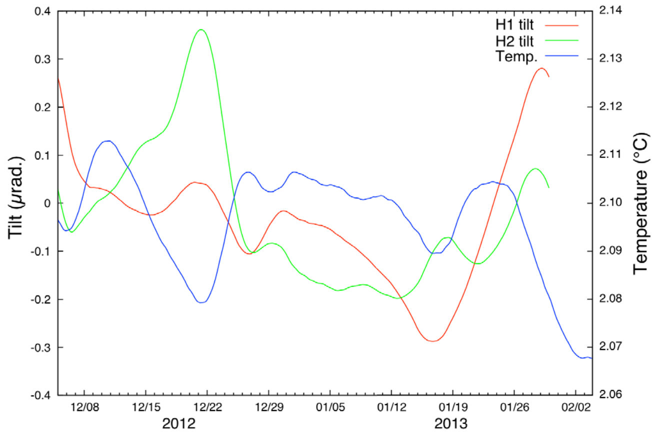


Fig. 3. Tilt variation in time obtained by the BBOBST-NX at the same site of the Fig. 2. The data was processed by using the baytap08 program to remove tide variation and moving averaged with the window of 7 days long. The water temperature data was obtained by the Doppler current profiler deployed nearby the BBOBST-NX. The averaged speed of the bottom current is about 5 cm/s (max. 13 cm/s). In this condition, tilt fluctuation was less than ±0.5 μ radian through the whole observation period. No apparent relation between tilts and the water temperature was observed.

recently. Because the sensor unit of the BBOBS-NX looks well coupled with the sediment, we have tried to check the performance as a tilt-meter.

The first test observation was performed at the land observatory in 2010. The result was comparable with that of the water tube tilt-meter installed in the same vault. After the in situ test for 2 months at the seafloor of the Shikoku Basin in 2012 (Fig. 3), we started the practical tilt observation at the seafloor off Boso peninsula (SE Honshu, Japan, KAP3 site) as the feasibility study between April 2013 and April 2014. The deployment and recovery were performed by the ROV, HYPER-DOLPHIN (JAMSTEC). In both observations, a Doppler current profiler was deployed nearby the BBOBST-NX to monitor bottom currents. In January 2014, a SSE of Mw 6.5 occurred close to the KAP3 site. The tilt data of the BBOBST-NX was processed through removing the trend of the mechanical relaxation by the curve fitting and tide signals by using the baytap08 program [9]. The result shows recognizable peak started from the late December 2013, but the tilt was not remained after the SSE ended. The maximum tilt is comparable to the theoretical value of a few μ radian, assuming a fault plane of Mw 6.5 at the plate boundary beneath the site. This BBOBST-NX system indicates the possibility of the tilt measurement in the shallow seafloor sediment, if the tilt occurred will be larger than about ±5 μ radian under the severe condition of strong bottom currents [10]. For more practical tests of this system, we have started two-year-long observations at two sites, off Boso and off Miyagi, in July and Sep. 2015.

III. Preparations for The Autonomous System

The BBOBS-NX (and BBOBST-NX) system must be a powerful tool to study dynamics of the Earth in seismology and also in geodesy, although, the current system has intrinsic limitation in opportunity of observations because of the necessary use of the submersible vehicle for the deployment and recovery. If we can operate this powerful system with almost any kind of vessels, like as the BBOBS (self pop-up system), it should lead us a true breakthrough of seafloor observations in geodynamics. Hereafter, we call this new autonomous BBOBS-NX as the NX-2G in short.

Through our 16 times operations of the BBOBS-NX including the BBOBST-NX until August 2015, we found following problems to be cleared to realize the NX-2G system:

A. Tilt of the sensor unit on landing

The first problem is a tilt of the sensor unit on landing, which is larger than the acceptable limit of the sensor (±8°) in 44 % after our 16 deployments until now (Fig. 4). In these cases, the tilt was corrected by using the skid of the ROV with the full down thrust. It was impossible to correct it by pushing the sensor unit with the manipulator. Unfortunately, we still have no evidence at which moment the tilt occurred. One example has been obtained when we tested the OBS for ultra-deep sea (NUDOBS) [11], which equips the MEMS accelerometer and worked during the deployment. This OBS has similar concept design to the BBOBS-NX, but it works as an autonomous system with a shallow penetration sensor package. Fig. 5 indicates tilt variation in time before and after the landing. In this case, there was tilt of about one degree just before the touch down of the sensor package to the seafloor, but the sensor package became almost vertical during the penetration into the shallow sediment. So, we will try to obtain the data of the descending and landing BBOBS-NX by attaching a video camera and an accelerometer logger, when we deploy the BBOBS-NX and the BBOBST-NX in Sep. 2015.

As possible solutions for this problem, 1) stabilizing the descending posture if the tilt had been occurred before the moment of the landing, 2) increasing the acceptable tilt limit of the sensor or use of the active leveling, or 3) adoption of a high

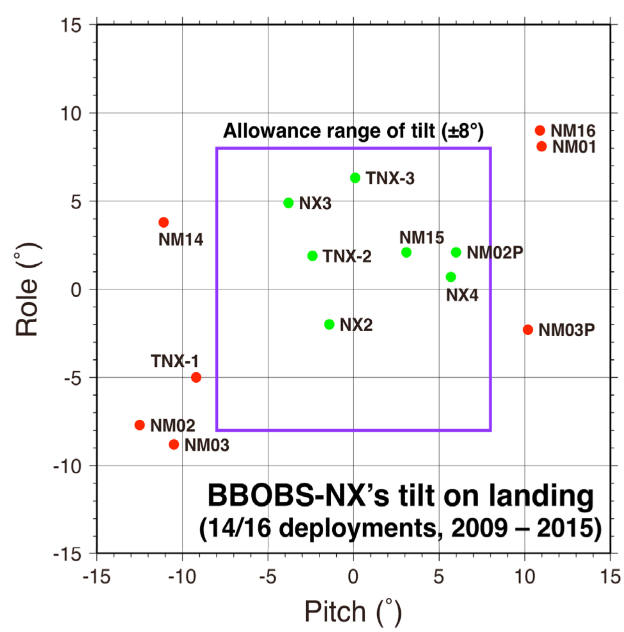


Fig. 4. Tilt values (pitch and role) of the sensor unit on landings (solid circles). The broadband sensor used in the BBOBS-NX works properly under tilts of less than ±8° indicated as the purple square. Labels denote each observation.

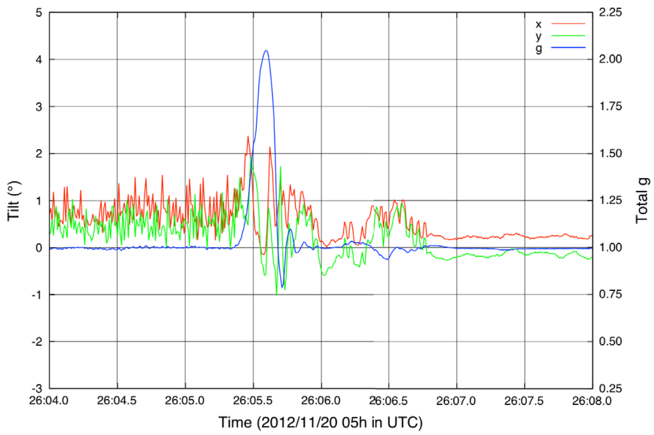


Fig. 5. Tilts (x and y) and the total g around the landing of the NUDOBS. The data was obtained by the 3 component MEMS accelerometer in the sensor package. The total g is a square-rooted squared sum of 3 component accelerations. The data was low-pass-filtered (44 Hz) and the full-scale was ±2 g in the MEMS accelerometer. The tilt in descending and the first touch to the seafloor was gradually corrected as almost tilt-less condition. As the construction of system is different from that of the BBOBS-NX, the landing process would not be same.

resolution acceleration sensor that can be used in any direction, are considered.

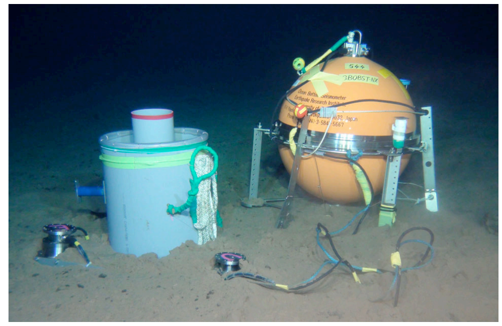
The first one would be realized by using an underwater robot, which is attractive but should be large and expensive. The second one is straightforward, but it might make difficult to achieve enough penetration of the sensor unit due to the larger diameter and taller height than the current system. The third one is good and simple, but specifications of the accelerometer should be well examined to keep low noise level observation in the long period range of the BBOBS-NX. We will start detail evaluations of the accelerometer using crystal resonators [12], which is small and very low power consumption.

B. Noise level in the new system

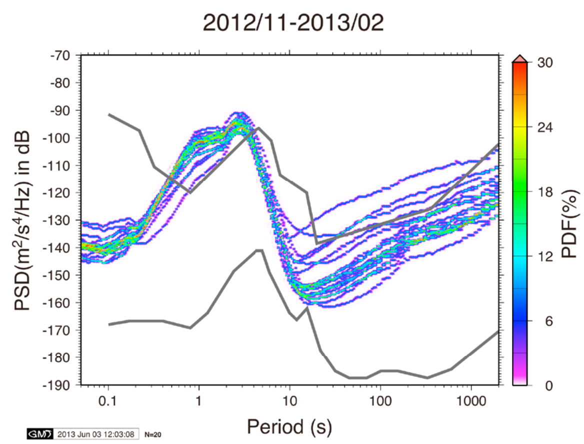
The second problem is the noise level of the new system, which should be the similar level with that of the current BBOBS-NX. Although we have not determined the final design of the NX-2G, an evaluation test was conducted by placing a large object inside of the sensor unit and the recorder unit nearby it too (Fig. 6a). At this test site in the Philippine Sea (about 4900 m depth), the noise model is obtained as we have been performed several long-term observations by using BBOBSs and BBOBS-NXs. The noise level in Fig. 6b shows no significant degradation under this test condition, which means the large object that exposed in the bottom current nearby the sensor unit could not become a serious noise source to the sensor as far as they were weakly coupled together via soft sediments. This result gives us flexibility to design the NX-2G system.

C. Extraction of the sensor unit

The third one is a required force to extract the sensor unit from the sticky clay sediment, which was about 75 kgw in maximum with the current BBOBS-NX system from in situ measurements (Fig. 7), although the weight in the seawater of the sensor unit is about 30 kgw. This value is not so large to realize the self pop-up recovery system, but we need to pay much attention to design the whole autonomous system for the reliable recovery. From another point of view, the use of a smaller accelerometer instead of the current broadband sensor should result easier extraction by using a smaller pressure case with a narrower diameter.



(a)



(b)

Fig. 6. The scene (a) and the noise level of one horizontal component (b) for the test with a large object near the sensor unit. A large PVC tube was put in the middle of the sensor unit, and the recorder unit was also located close to it unusually. The noise level result shows no clear degradation with this condition, as it is below the NHNM generally.

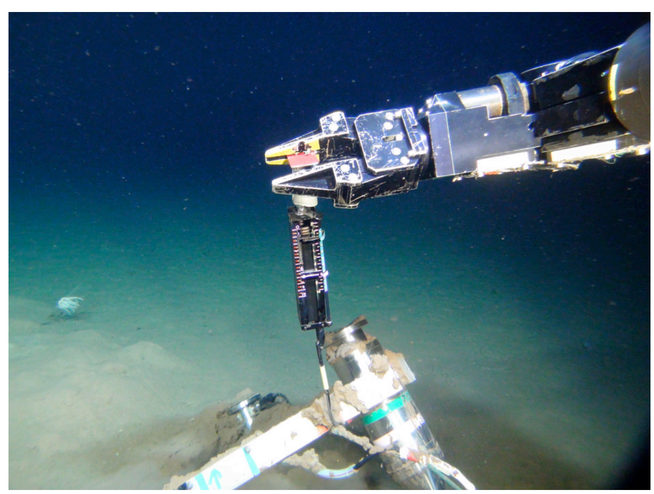


Fig. 7. In situ measurement of the extraction force of the sensor unit from the sticky clay sediment. The special scale used was made for this measurement.

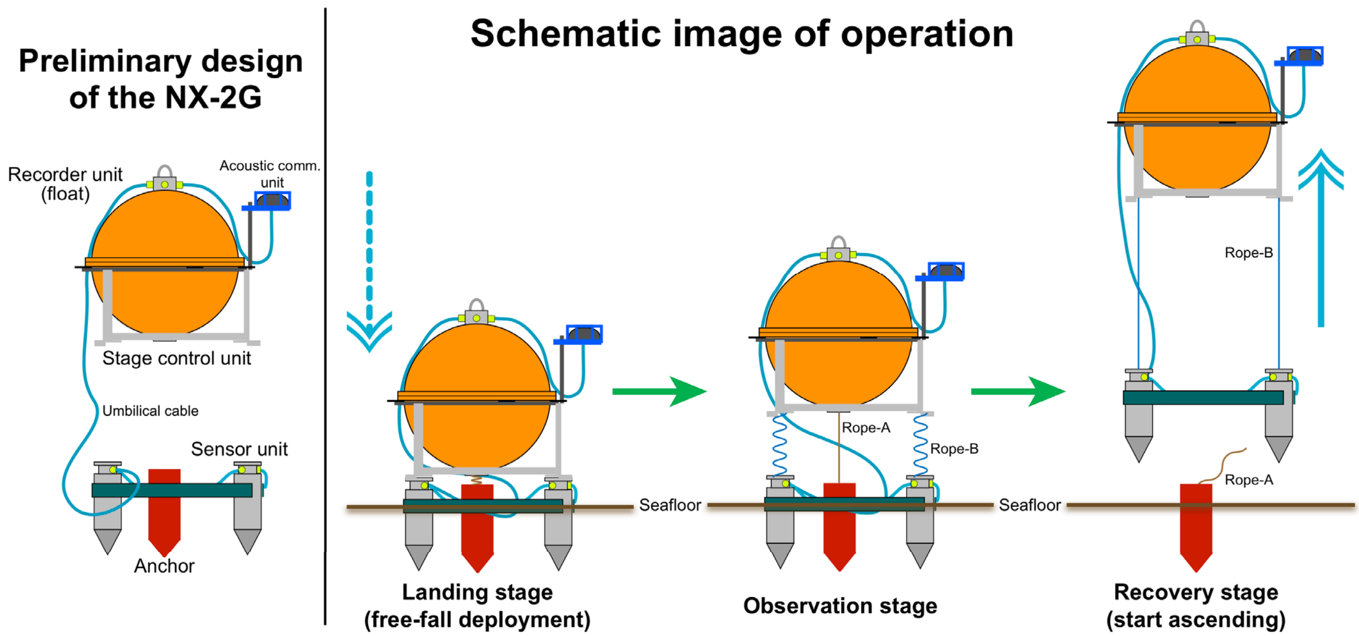


Fig. 8. The preliminary design and the schematic image of operation of the NX-2G system. This construction is an idea of the autonomous BBOBS-NX without quantitative considerations. Three stages are controlled by using the stage control unit and rope-A/B, through the acoustic transponder system.

IV. Basic Plan of The NX-2G

The image of the NX-2G is shown in Fig. 8, which has three stage operations like as the current BBOBS-NX system. The core unit to perform these operations has been already developed for the NUDOBS system in 2012 [11], which will be installed at the bottom inside of the lower hemisphere of the housing. When we deploy the NX-2G, in the landing stage, the sensor unit, the recorder unit and the anchor are mechanically connected to achieve enough penetration into the sediment. During the observation stage, the recorder unit and the anchor are connected via the rope-A in Fig. 8, but the sensor unit has no rigid coupling with others. As noted in the previous section, some part of the anchor will be located inside of the sensor unit triangle, but they are almost decoupled each other to prevent the seismic noise induced by the bottom current. At the recovery stage, the connection with the anchor is released for ascending with extraction of the sensor unit. The first prototype NX-2G will be tested in 2016 with in situ observation of operations among three stages from a submersible.

V. Summary

Based on experiences of the BBOBS development and observations since 1999, we made the BBOBS-NX and the BBOBST-NX for researches of time axis range not only in seismic but also in geodetic periods now, with data quality of comparable to land stations. There are still some difficulties that should be solved to realize the autonomous system, NX-2G, it will become a necessary tool to perform seafloor seismic and geodetic observations to study the Earth interior by usual temporal experiments. As we have a financial support (JSPS KAKENHI) for this NX-2G development from this year, we are going to realize this new system within 5 years.

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