Marine Search-and-Recovery Operation of Scientific Balloons in Japan

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Stratospheric balloons have been used worldwide for more than half a century for various scientific missions. However such balloon operations are facing safety issues due to the reduction in appropriate sites for landing. Instead of landing on the ground, landing and recovering on the sea can be a radical solution to this problem. Marine search-and-recovery operations for balloons are not conducted commonly; however, such the operation has been uniquely developed in Japan for more than 40 years. This study describes the methodology for such search-and-recovery of balloons and gondolas through examination of multiple case studies.

Keywords: Balloons.

1. Introduction

Stratospheric balloons have been operated worldwide for more than half a century and have contributed to the progress of space science. One of the attractive characteristics of such balloons is their recovery. The scientific payloads are parachuted from the stratosphere to the Earth's surface after the completion of their missions, and are then recovered. Through this recovery, scientists can easily obtain a huge amount of raw observational data without radio communications. Some of the recovered on-board devices can be reused in other balloon missions, reducing the mission-development cost.

Many balloon recoveries are conducted on the ground. However, the ground area suitable for

balloon landings has gradually grown smaller. One of the advantages of the balloons is that they can carry a heavy payload at a small cost. Some payloads weigh more than one ton. Moreover, some of the balloon envelopes themselves weigh more than several hundred kilo-grams; however, they cannot propel themselves or move to a safe landing site. Therefore, wide and sparsely populated areas are necessary for safe balloon landings. On the other hand, suitable areas have decreased in size and number due to the increase in population and the expansion of suburban development. Figure 1 shows the population-density map of the world from the “March 2015 revision of the World Population Prospects of the United Nations” (Center for International Earth Science Information Network (CIESIN), Columbia University, 2016). The brighter areas show low-population density areas which seems suitable for balloon landings. However, such areas are difficult to access due to precipitous

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Fig. 1. Population density in 2015 (Center for International Earth Science Information Network (CIESIN), Columbia University, 2016).

landscapes, dense forests or distance from a town to be a temporary staging point.

Recently, for ensuring safety and sustainability, studies of the methodology of marine search-and-recovery of balloons are beginning. Although marine search-and-recovery operations have not been common, such operations have been conducted in Japan for many years. The balloons launched in Japan descended mainly onto the ground during the 1950s and 1960s, nevertheless a balloon mission with a heavier payload was already planned to descend into the ocean to enhance safety in the latter half of 1960s (Minagawa, 1966). The necessity of marine recovery rapidly increased in early 1970s due to the increase of heavy payloads. In 1974, many balloons and payloads were guided toward the ocean and for recovery in order to avoid increasing air traffic around the launch site (Nishimura, 1974). Many efforts were made toward the development of marine-recovery technology, such that the sea became the main drop area for Japanese scientific balloons at the end of the 1970s (Nishimura, 1979), and technologies have developed further since then. Consequently, Japanese balloon operators have accumulated unique experiences and understanding of marine operations for balloon recovery over more than 40 years.

This study addresses the methodology of the sea-recovery operation of stratospheric balloons based on Japanese experience and knowledge. The next section discusses the characteristics of recoveries on the sea that are different from those on the ground. In the third section, a recovery operation in Japan is introduced as a case study. The last section summarizes this study.

2. Differences to be Considered

2.1. Environment

2.1.1. Necessity of floating

The most remarkable difference between recovery operations on the sea and the ground is the necessity of floating. Only objects with larger buoyancy than their mass can stay on the sea surface, although anything can stay on the ground without special equipment. Once the payloads sink in the ocean, the search-and-recovery operations become much harder. Hence, buoyancy management on the sea is the most important issue for the sea-recovery operations to retain the gondola on the sea surface.

The gondola can be attached to a floating device; however, working with balloon envelope is more difficult. Many envelopes made in Japan retain on the sea surface after splashdown. An envelope contains a certain amount of air by being entangled during descent. Owing to the light weight of the envelope, e.g. a 100,000-m³ envelope with a mass of approximately 300 kg, it can retain on a calm sea surface for a while under its own buoyancy. However, it will sink when it loses the air inside due to strong waves. Fast access to the envelope is required for balloon-envelope recovery.

2.1.2. Drift

Another difference is drift. Payloads and balloon envelopes on the sea are moved by wind and tides more easily than those on the ground. The payloads and envelopes can drift more than a few tens of kilometers in a single day, as shown in Fig. 2 (Toriumi et al., 2003). Therefore, the landing point should be carefully selected when there is a restricted area such as a border or fishing net near the estimated landing point.

Fig. 2. Trajectory of a gondola drifting on the sea in 49.5 h. (Toriumi et al., 2003)(translated by author).

As mentioned above, a balloon envelope can retain on the sea surface; however, it quickly loses buoyancy on a rough sea surface and sinks. Once it sinks, it will be caught by tide under the sea, making it very difficult to recover. Agile search-and-recovery operations are necessary for balloon-envelope recovery.

2.1.3. *Waving and tumbling*

The disassembly of the gondola at the landing site is one of a common recovery method on the ground. However, on the sea, such processes will face greater difficulties and risks. Gondolas on the sea are subject to waves, which reduce workability. The gondola may tumble when it loses its balance as the recovery crew attempts to access it, and the access points on the gondola are not always above the sea surface. A better procedure is to perform only safety matters when the gondola is on the sea, and to do precision work only after bringing it to the land or a stable deck of a large vessel.

2.2. *Electric and chemical conditions*

2.2.1. *Electrical shortage*

Sea-water is an electrochemically active liquid. The electric wiring and power management of the flight system should be carefully designed. The electrical resistance of sea water is much smaller than that of fresh-water; therefore, a large electric current is passed easily through sea-water over distant contacts. If a pair of a battery terminals led out of the battery enclosure under sea-water, the battery will continue outputting current until it runs out, or until the current path is broken.

2.2.2. *Corrosion*

Sea-water causes electrochemical corrosion of metal materials. Connector contacts through which electric current paths are corroded. The gondola structure or casings of devices comprising electrically conductive materials can form current paths when they are connected to the electric circuit as an earthing layer or a frame ground. Two different metal materials placed near each other in sea-water also constitute a voltaic battery and generate a small electric current, causing corrosion of the metal material of the structure. The devices to be reused for another balloon flight should be appropriately protected from sea water.

3. Case Study

In this section, the Japanese balloon flight-system for marine recovery is introduced as a case study.

3.1. *Surrounding environment*

Here, we describe the surrounding environment, particularly in terms of marine search and recovery of the balloons. The example in this section is the case of operations around Taiki Aerospace Research Field (TARF), a Japanese balloon base run by the Japan Aerospace Exploration Agency (JAXA) in Hokkaido, Japan. For general descriptions of the TARF, refer to the research by [Fuke \(2010\)](#). The map around the operational area is shown in Fig. 3. The operational area for the search and recovery is located to the northwest edge of the Pacific Ocean, which is to the east of the TARF. The base port is the Taiki port located on the coast-line near the TARF, and we hire fishing boats at the port as search-and-recovery vessels under normal operations. The gray area in Fig. 3 shows the basic area for search-and-recovery operations. The area is approximately 10 nautical miles (NM; or approximately 18 km) from and along with the coast with a width of approximately 10 NM. We avoid landing balloons within 10 NM of the coast for safety because this region is a popular fishing area and is therefore crowded with fishing boats and nets. The eastern limit of the area is defined due to the domestic legal classification of the boats, and the northern and southern limits are defined based on the boats' cruising radius. In some operations with larger balloons that cannot be salvaged by fishing boats, we hire larger vessels from the other ports. These are the basics of the operations off the coast near the TARF; however, when the other areas are defined as search-and-recovery operational areas, other ports and appropriate vessels will be selected.

There are two types of the fishing boats at the port that are available for these operations. Table 1 summarizes the specifications of each type. One type is boats with low freeboards and powered cranes. Low freeboard makes access from boat's deck to floating bodies so easy that this type of the boat is used for salvaging large bodies. The other type is boats with high freeboards, which are used mainly for performing search operations. When the objects to be recovered are small, this type of boats can also be used for salvaging. The cruising speed of

Fig. 3. Map of the search-and-recovery area.

Table 1. Types of the fishing boats for search and recovery.

Type of vessel	Low freeboard	High freeboard
Main role	Recovery of heavy objectives	Search (and recovery of light objectives)
Deck size	21 × 4.4 m	12.5 × 3.2 m
Speed (cruise/maximum)	approx. 10/17 knots	approx. 10/19 knots
Equipment	Powered crane	
Outlook

both types is approximately 10 knots or 20 km/h. They reach any stand-by points in the area within approximately 2.5 h. Additionally, a helicopter assists in the search-and-recovery operations when the weather satisfies the conditions of the visual flight rules (VFR). The TARF is capable of parking and refueling the helicopter.

As mentioned above, the search-and-recovery area is contained in a good fishing area, and thus, there can be many fishing vessels even from the ports other than Taiki. We inform the local fishery associations, the Japan Coast Guard, and even the other fishery associations having vessels working in the search-and-recovery area about our balloon operations in order to safety and alert these organizations.

3.2. Policy

Balloon search-and-recovery operations are conducted according to the following policies, which are formulated to maximize the safety and sustainability of balloon operations in the region:

- Both the gondola and the balloon envelope including non-reusable parts must be quickly recovered in order for the nature conservation and for the safety of the marine traffic and the fishery industries, as well as for the success of the mission.
- The priorities are as follows:
 - (1) Search for the gondola.
 - (2) Search for the envelope.
 - (3) Recover the gondola.
 - (4) Recover the envelope.

Confirming the positions of the envelope and the gondola is the first step of recovery. Once the envelope sinks, it will pollute the sea. The envelope should thus be found before it sinks.

- The operation must be conducted within 20 NM of the coast due to legal restrictions.
- The operation should be done during the day.

3.3. Flight system

3.3.1. Float

Float is the most important part of the gondola for sea recovery because it defines whether the gondola can be recovered as well as the safety of the recovery operators. Therefore, float of the gondola should be carefully designed.

The basic float design starts with the estimation of the necessary buoyancy. The buoyancy should support the maximum mass of the gondola. Our float design policy in Japan regards “the maximum mass” including the mass of the ballast. This is a safe design in case for the flight termination is accidentally performed earlier than the flight plan, because Japanese balloons start flying over the sea soon after launch, carrying most of their ballast. As a result, gondolas are equipped with much more buoyancy

when the balloon is normally operated and when all the ballast has been dropped. We accept the excess buoyancy as a safety factor. The float is usually fixed to the gondola by bonding and glass-fiber tape. This technique closes the gondola and makes it difficult to access its interior. Recently, some gondolas have applied screws to fix the float to the gondola frames supported by metal adapter plates.

A better float design carefully arranges the float blocks in a gondola considering the attitude of the gondola floating on the sea. The gondola is often defined a preferred floating attitude on the sea for the ease of the access to the gondola; one of such requirements is to bring the access point above the sea surface. The attitude of the gondola is defined by the arrangement of its center of gravity and the volumetric center of the float under water. Therefore, the float arrangement defines the workability of the recovery on the sea; and careful design is recommended. Figure 4 shows an example of the float arrangement on a gondola with an astronomical telescope (Shoji *et al.*, 2012a). The gondola comprises some of several tens kilo-grams devices and the 280-kg-ballast storage in the lower part. The center of gravity of the gondola is located in the upper part after the ballast has been completely dropped. In Fig. 4, the red parts show the float

Fig. 4. Float (red part) arrangements in a gondola.

blocks, and marks indicate the approximate positions of the volumetric centers of the float blocks. The float blocks are arranged to support each partial mass of the upper, the middle and the lower parts of the gondola. As the result, they produce the buoyancy twice larger than the nominal mass of the gondola on the sea with the half of the gondola above the sea surface.

Selecting an appropriate float material is also important. Generally, there are many kinds of polystyrene foam with particular densities and manufacturing methods. Usually, we use expanded polystyrene (EPS) foam with a density of 25 kg/m^3 which provides 975 kg of buoyancy with a volume of 1 m^3 . Extruded polystyrene (XPS; known as “Styrofoam”), another kind of foamed styrene, can be float as well. Floats on gondolas have been made from these materials in Japan for a long time. However, in the case where other foamed plastics are considered for floats, careful verification is necessary. The strength of the material is another important factor. The float must not be broken by the impacts of splashdown or waves during floating. The impact acceleration can be greater than 25 G depending on certain factors after a descent rate of 5–7 m/s by parachuting. The materials we use are recommended in general industrial usage for cases of medical items or cushioning of heavy items and have functioned well in balloon operations. Strength depends on the shape of the material; therefore, block shapes are favorable. Reinforcement of the float with glass fiber tapes is a good way against broken.

Some foamed plastics would expand under low air pressure and compressed under high pressure owing to the micro structure of the foam. Such materials are not preferred for floats because floats might be deformed in the stratosphere and lose their buoyancy. Floats are the essential in the marine search-and-recovery operations: therefore, thorough investigation is required when new materials are introduced.

Someone would find an airtight case or a water resist case like ones mentioned in the following section can be a part of the float. Indeed, such the cases will provide the buoyancy under the water. However, the risk of the leak must not be under-rated. In the same sense, airbags can be a good float, as applied to the re-entry capsules of the Apollo program, which are small in the flight and expand on the sea to produce large buoyancy. But the risk

of the leak is as well, and what is worse is that they might be easier to be damaged than solid floats. The one of the advantages of balloons is more moderate restriction on the volume of the payloads. Therefore, we consider the safer is to gain the buoyancy with the independent solid float.

3.3.2. Water-resistant cases

An airtight case is often used to maintain the air pressure around some onboard devices. It is also a good solution for protecting devices from sea-water. Another reasonable solution is the use of water-resistant cases of which many are commercially available. However, careful environmental testing is recommended. Some cases without high-pressure resistance can suck the water inside after a flight. The rubber seal often forms a narrow gap with the case because the seal shrinks and hardens in cold air, causing air to leak. The seal recovers in the warmer air in the level altitude and the sea surface with the air pressure inside negative to surroundings and the water seal capability weaker. It would be useful to evaluate water-resistant cases under pressurized water.

3.3.3. Hook point for hoisting

The gondola is hoisted up by the crane of the vessel when it is recovered. The connecting point between the gondola and the suspension is reasonable for hooking, but the point is often under water. Additional hook points would be useful in case the gondola floats on the sea upside down. A larger hook ring is often helpful for recovery operations on heavy seas.

3.3.4. Appearance

Many balloon gondolas are painted white in order to control the thermal input from the Sun. The white structure appears highly contrasted on the sea from a distant position or from the sky during the search operations under clear weather. However, under bad weather conditions, such as high waves with whitecaps or foggy areas, pure white gondolas will blend into the environment and loses their visibility. One good way to improve the visibility is to paint the gondola a vivid color such as orange. It may also be a good idea to paint the gondola in a geometric pattern such that does not blend into the natural patterns on the sea (Fig. 5).

Fig. 5. The parachute (left) and the orange-and-white checked gondola (right) on the sea.

Another way to improve visibility is to use a sea marker, which is a kind of vivid fluorescent pigment distributed in sea water, to change the color of the sea surface. Sea markers are widely used in water-flow research and in marine salvages; therefore, many commercial products are available. The use of a sea marker should consider following factors: the sea marker is scattered on the sea surface, hence improving visibility from the sky, it is particularly effective for search operations with aircraft support, and it may lose its density after several hours due to waves and tides. The balloon-flight, search, and first-vessel-access operations are planned to be conducted in the hours following splashdown.

3.3.5. Positioning buoy

The key device for the positioning of the drifting gondola is the positioning buoy. We have developed devices that can remotely identify the location of the gondola on the sea. This development started at the end of the 1990s with the GPS and the NOAA/ARGOS (Nishimura, 1998) and became operational in 2001 (Toriumi *et al.*, 2003). The improvement and development have continued. Consequently, today, we operate another positioning buoy system with the GPS and the Iridium satellite communication (Shoji *et al.*, 2012b).

The Iridium buoy comprises a GPS receiver and the Iridium satellite data communication transceiver. The buoy identifies its position and transmits position information to the balloon's base every 5 min with the most frequent setting. The information reaches the base through the Iridium network and the Internet within 5 min or less under good communication conditions. One of the

Fig. 6. Sphere Iridium buoy.

advantages of the Iridium buoy over conventional positioning devices is that no special ground stations are required. The telemetry can be received through the Internet as multiple e-mails. Remote commands to the buoys that switch their sampling frequencies are sent as well.

We currently use three types of Iridium buoys. One is the basic spherical buoy (Fig. 6). It is a commercially available product of Zeni Lite Buoy Co., Ltd, which is brought to the recovery object by the search boat, and tied to the objective to watch its position from the base in case recovery cannot be performed quickly. The buoy contains a lead battery and a solar cell, enabling continuous operation for a long time.

Another type of buoy is the balloon-flight buoy (Fig. 7), which is standard for domestic balloon flights. It can operate from sea level up to the stratosphere, reporting the position of the gondola, including its altitude in every 5 min. The buoy has dimensions of approximately $\phi 220 \times 750$ mm and a mass of 5.8 kg. It is tied to the surface of the gondola with rope and separated at splashdown by cutting the rope with an explosive. The buoy is connected to

Fig. 7. Iridium buoy for flight.

the gondola with another 5-m-long rope and holds the antennas above the sea surface regardless of the gondola's attitude. The buoy survives for more than 10 days with a nominal reporting rate that can be remotely changed, and the survival duration can be extended with a less-frequent transmission rate.

The final type is the mini buoy (Fig. 9), which was recently developed based on the standard flight buoy for smaller gondolas, with a length of 400 mm and a mass of 1.5 kg. The functions are simplified, and the buoy is made much lighter than the standard buoy owing to its polycarbonate body, compared with the standard buoy which is made of aluminum. This buoy survives for approximately 2.5 days, reporting on its position every 5 min; its life can be extended by extending the report interval longer as well as the other two types.

3.3.6. Radio beacon

Before the positioning buoy with satellite communication was developed, a radio-beacon buoy was used. This beacon buoy transmitted a radio signal after the splashdown of the payload, which was then received by recovery vessels and the ground station. This buoy has been replaced with the current technique because the coverage of the beacon buoy which was limited to only the visible area. However, beacon buoys are often equipped with payloads that with which it would be difficult to equip the current positioning buoy due to its operation conditions such as size and mass as well as its aerodynamic shape. The beacon buoy is also useful in sea areas where Internet access is unavailable.

3.3.7. Flash-light

We also equip the buoy with a flash-light for better night time visibility. The gondola may drift on the sea toward coastal areas, although the splashdown point is located in a low-traffic area away from the coast. Since fisheries operate in coastal areas, traffic may be crowded, particularly during the night. Better visibility at night is important for the safety of both the gondola and the traffic.

3.3.8. Siren

The landing area for the balloons is selected so as to be distant from the populated marine areas; however, there may be ships because the area is not restricted. As shown in Fig. 8, a siren is mounted on the gondola in order to warn such ships.

Fig. 8. Iridium buoy for flight attached to the gondola.

Fig. 9. Miniature Iridium buoy.

3.3.9. Sea-water battery

Sea-water batteries are used to fire the rope cutter to cut the rope tying the buoy to the gondola. This battery comprises a voltaic cell when it is under the sea and then generates approximately 1 W of electricity to fire the cutter. We mount two sea-batteries on the bottom of each gondola as a redundant pair, which is expected to sink under the sea during splashdown.

3.3.10. Water-soluble string

Another way to release something tied to the gondola is to use water-soluble string. This string is used in dry air like cotton string; however, it becomes weak and dissolves in water. This is a useful material because it does not require any additional parts to function unlike the rope cutter, which requires batteries, a water detector, and power-switching mechanisms. On the other hand, this string is not as strong as ropes made of material such as nylon. Water-soluble string is suitable for

tying up light weight objects, such as using a rolled mooring rope to tie the buoy to the gondola.

3.3.11. Design based on reusability

One of the issues on the design of the marine-recovered gondola is sorting of the parts according to reusability. As mentioned in the Sec. 3.2, all the parts concerning to the heavy balloon must be recovered. The parts of the flight system exposed to the environment cannot usually be reused due to damage by the corrosive sea water, although the parts inside the water-proof cases may be reused. Such the environmentally exposed parts are recommended to be selected from low-cost and easily available items when the flight system is intended to experience multiple flights and marine-recoveries. For example, the gondola with an astronomical telescope shown in Fig. 4 stored special and expensive optical devices inside airtight cases. On the other hand, the telescope tube and the mount which was not protected from the sea water was selected from commercially available ones in order to be renewed easily for the following campaigns.

3.4. Operation

3.4.1. Organization and operation sequence

One search-and-recovery party comprises of three fishing boats and a helicopter. Table 2 summarizes the party. Every boat belongs to the Taiki port and is operated by local fishermen who know the area and the work well. Low freeboard boats, which can easily reach near the sea surface, are assigned the recovery of the gondola and the envelope. The boat

for the gondola also takes the mission scientists along as on-site deciders about the gondola. High freeboard boat searches for the gondola and the envelope. The types of the boats can be switched depending upon the recovery target. The helicopter mainly engages in the search for the envelope which is more difficult than that for the gondola, as described in Sec. 3.4.3. Its speed and high view point are strong supports for boats. The helicopter also often performs as a payload carrier; it can be attached a cargo hook and can bring the payload back to the TARF.

Each member of the party is under the guidance and control of the TARF. Basically, the guidance information is sent to the vessels via e-mail with the Iridium satellite cellphone (shown as “IrTEL” in Table 2). Character-based communication is effective in our operation because viewing messages is a reliable way to communicate under excessive boat-engine noise.

The boats for the balloon envelope that cannot be equipped with Iridium buoys carry the Iridium-sphere buoys (shown as “IrB” in Table 2). On the other hand, the boat assigned to the gondola also carries an Iridium locator (“IrL”). This cannot float on water; however, it functions as well as the Iridium buoys. Before reaching the recovery objectives, the buoys on the boats report the boats’ positions as their normal function. This is very helpful for guiding the boats in the search-and-recovery area. Instead of an Iridium buoy to tie the gondola (which is already equipped with a flight buoy), the boat for the gondola is equipped with the Iridium locator.

A search-and-recovery operation normally progresses along the schedule summarized in Table 3. The *X*-time is defined as the flight termination, and

Table 2. Example assignment of recovery vessels for one operation.

Role	Recovery of the gondola	Recovery of the envelope	Search of the gondola and the envelope	Search of the gondola and the envelope
Type	Low freeboard	Low freeboard	High freeboard	Helicopter
Character	Powered crane	Powered crane		Payload suspension (optional)
Crew	Captain, RP ^a , Scientists×1–2, Support crews ≥ 3	Captain, RP, Support crews ≥ 3	Captain, RP, Support crews×1–2	Pilot, co-pilot, RP
Equipment	IrL ^b , IrTEL ^c Gondola fixing stage	IrB ^d , IrTEL	IrB, IrTEL	Downlink radio receiver

Notes: ^aRecovery professional.

^bIridium locator.

^cIridium cell-phone.

^dIridium sphere buoy (Fig. 6).

Table 3. General search and recovery operation sequence.

Time to separation (min.)	Operation
$X - 180$	Latest prediction of the land point informed to the recovery team Departure of recovery team
$X - 60$	Stay at stand-by points
$X - 15$	Buoy operation begins
X	Gondola separation Each latest stand-by point informed to the recovery team Moving to the stand by points
$X + 50$	Balloon-envelope splashdown Balloon search boat moving to the envelope land point Balloon recovery boat moving to the envelope land point
$X + 60$	Gondola splashdown Gondola recovery boat moving to the envelope land point Gondola captured Balloon envelope captured
$X + 80$	Search boats return to the port Gondola recovered on the boat and returns to the port
$X + 110$	Balloon envelope recovered on the boat and returns to the port
$X + 200$	Gondola returned to the port
$X + 230$	Balloon returned to the port

the operation starts approximately 3 h before the X -time because traveling to the farthest stand-by point in the operation area (shown in Fig. 3) requires more than 2 h. The recovery vessels start moving at the X -time according to the guidance from the TARF. Recently, the first access to each objective has been conducted within 15 min following splashdown on average and the recoveries are completed within 60 min. The duration of the search has been drastically shortened over the last 10 years. This is largely owed to the Iridium buoys, which enable accurate guidance to the gondola, even under dense fog.

3.4.2. Payload-recovery procedure

The recovery of the gondola usually begins with access to the parachute. During the approach and the recovery operation, the vessel stops the screw. Strings on the flight system under the sea are the risk; they may wind in the screw and the shaft. The parachute is hooked with a rod with a hook from the deck, after which the parachute and the suspension rope are pulled by hand and stored below

Fig. 10. Recovery process of the parachute.

the deck (Fig. 10). Next, the crew pulls up the hook point on the gondola (Fig. 11), connects the point to the crane, hoists the gondola (Fig. 12), and puts it on the deck. The remaining accessories, such as the buoy, are recovered. After the gondola is fixed onto the deck, the least processes for the safety such as turning off the system or removing the primary batteries wet with sea-water are conducted before the vessel leaves the point for the port. Such a normal recovery operation requires approximately 10 min from the first access to the parachute to the completion of the safety process.

To access the parachute first, we attach a float at the inside of the top of the parachute with buoyancy larger than the mass of the suspension. Otherwise, the parachute will be drawn into the sea by the suspension and will become a sea anchor.

Fig. 11. Access to the gondola.

Fig. 12. Recovery process of the gondola.

In this process, we should pay extra attention when hoisting and lowering the gondola. The roll and pitch motion of the vessel significantly swings the hoisted gondola with a mass of several hundred kilo-grams. This motion depends upon the size of the vessel. We usually limit the wave height to 2 m or less for safe operations.

3.4.3. Recovery procedure of the balloon envelope

The recovery of a balloon envelope is conducted as well as that of a gondola. However, the envelopes are usually collapsed at the flight termination and get entangled during descent. Search-and-recovery operations for balloon envelopes are much more difficult than those for the gondolas.

In Japan, the landing point of the envelope is estimated based on both GPS telemetry and the radio tracking from the TARF. The search-and-recovery vessels are guided to the estimated landing point, and the descending envelope is sometimes detected by the radar on the vessel just before the splashdown if the envelope reflects the radar's radio wave. A helicopter is also useful to search for the envelope in the sea. The envelope after the splashdown cannot remain above the sea surface and floats flatly (Fig. 13), thereby reducing envelope's visibility from distant places. The envelope spreads along to the sea's surface such that an aerial viewpoint offers a good solution. In this case, the helicopter reports the position of the envelope to the TARF and the vessels and then remains in position until the vessel arrives. The vessel accessing the envelope approaches from the windward side and

Fig. 13. First access to a 300,000 m³ envelope. Fig. 14. A 15,000 m³ envelope on the sea (from a helicopter).

stops the screw. The approach to the envelope should be performed more carefully than that to the gondola because the parts of the envelope might spread under the water (Fig. 14) and could easily be tangled by the screw.

Envelopes can be salvaged depending on their size. Small envelopes, i.e. envelopes smaller than 15,000 m³, can be salvaged by hand. Larger envelopes are salvaged with an on-board crane. Figure 15 shows the sequence of envelope salvage with an on-board crane. First, a part of the envelope is hooked and hoisted by the crane onto the vessel (Fig. 15(a)). The part of the envelope is laid on the deck with a sling belt or wire rope beneath it (Fig. 15(b)). Then, the envelope is hoisted again with the sling belt and brought onto the deck (Figs. 15(c) and 16). The whole envelope is finally brought onto the deck after this sequence is

Fig. 15. Envelope recovery sequence.

Fig. 16. A fish boat salvaging a 15,000 m³ envelope.

repeated (Fig. 15(d)). To recover of larger envelopes, larger vessels is hired like the crane ship shown in Fig. 17. Although the crane is larger, the recovery is conducted in almost the same sequence.

Fig. 17. A crane ship salvaging a 300,000 m³ envelope.

4. Summary

In this study, the methodology of the marine search-and-recovery operations of stratospheric balloons is addressed. There are multiple differences between the ground and marine operations. This research reports ways to overcome the differences based on the experiences of the Japanese balloon operations. We hope that the marine-recovery technology of the stratospheric balloons progresses further, and expanding the opportunities for balloon flights and making further scientific contributions.

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References

- Center for International Earth Science Information Network (CIESIN), Columbia University [2016] “Gridded population of the world, version 4 (GPWv4): Population density adjusted to march 2015 revision of UN WPP country totals,” <http://dx.doi.org/10.7927/H4HX19NJ>, Accessed Sep. 9, 2016.
- Fuke, H. [2010] *Adv. Space Res.* **45**, 490.
- Minagawa, O. [1966] “Report on the 4th balloon campaign in 1966,” in *Balloon Symposium*, 28 November 1966, Vol. 1966 (Inst. Space Astronaut. Sci. Tokyo), pp. 22–30 (In Japanese).
- Nishimura, J. [1974] “Report on the balloon campaigns in 1974,” in *Balloon Symposium*, 12 December 1974, Vol. 1974 (Inst. Space Astronaut. Sci. Tokyo), pp. 1–8 (In Japanese).

- Nishimura, J. [1979] "Report on the balloon campaigns in 1979," in *Balloon Symposium*, 17 December 1979, Vol. 1979 (Inst. Space Astronaut. Sci. Tokyo), pp. 1–9 (In Japanese).
- Nishimura, J. [1998] *Adv. Space Res.* **21**, 931.
- Shoji Y. *et al.*, [2012a] "A balloon-borne telescope for planetary observations," *39th COSPAR Scientific Assembly*, PSB.1-0032-12.
- Shoji Y. *et al.*, [2012b] "The new positioning buoy for sea recovery operations in japan," *39th COSPAR Scientific Assembly*, PSB.1-0039-12.
- Toriumi M. *et al.*, [2003] "GPS Argos System," in *The Institute of Space and Astronautical Science Report SP*, Vol. 45 (Inst. Space Astronaut. Sci.), pp. 11–22 (In Japanese).