Recovery of the GSLV debris from the shallow waters of the Bay of Bengal, off Sriharikota, Andhra Pradesh, India

Ravi Mishra[1,*] and M. Sudhakar[2]

[1]National Centre for Antarctic and Ocean Research, Headland Sada, Vasco, Goa 403 804, India
[2]Ministry of Earth Sciences, Block-12, CGO Complex, Lodhi Road, New Delhi 110 003, India

The Geosynchronous Satellite Launch Vehicle (GSLV) launched from SHAR, Sriharikota on 10 July 2006 fell into the Bay of Bengal due to failure of the first stage L-40 engine. Search for recovering strap on engine(s) for conducting failure analysis was undertaken. *Sagar Kanya, Sagar Purvi* and *Sagar Paschimi* – the vessels of the Ministry of Earth Sciences, Government of India, and *Akademik Boris Petrov*, a research vessel that was hired, were deployed in search and recovery operations. Methods adopted for search were swath bathymetric surveys, side scan sonar surveys, underwater videography and search by remotely operated vehicles. Divers guided by survey results, recovered three engines and parts of a fourth engine within 100 days of the mishap from 10 to 30 m depth in the Bay of Bengal.

Keywords: Debris recovery, geosynchronous satellite, side scan sonar, swath bathymetry.

THE Geosynchronous Satellite Launch Vehicle (GSLV) is an expendable launch system used to launch INSAT-type satellites into geostationary orbit. It is a three-stage launch vehicle that uses four L-40 liquid strap boosters. During the launch, it is propelled by solid fuel in the first stage, liquid hypergolic fuel during the second stage and liquid cryogenic fuel during the third stage (http://www.isro.org/launchvehicles/gslv/gslv.aspx). The fourth flight – GSLV-F02 on 10 July 2006 was unsuccessful. Both the rocket and the satellite were destroyed and fell into the Bay of Bengal within minutes of the launch. A defective propellant regulator of the fourth strap on motor caused asymmetric thrust on the vehicle (http://www.isro.org/pressrelease/scripts/pressreleasein.aspx?Sep06_2006), steering it off course and consequently the self-destruct feature was deployed as a safety measure. All the debris fell into the Bay of Bengal, approximately 6 km from the shore, where the depth to the sea bottom was in the 10–30 m range. Figure 1 *a* shows the location of the debris fall.

L-40 engines had to be recovered to examine the cause of failure. The Ministry of Earth Sciences (MoES), Government of India (GoI) took up the task. The National Centre for Antarctic and Ocean Research (NCAOR), the National Institute of Ocean Technology (NIOT) and the Indian Space Research Organisation (ISRO) participated in this major operation, with NCAOR taking the lead. MoES vessels ORV *Sagar Kanya*, CRV *Sagar Paschimi* and CRV *Sagar Purvi* and a chartered vessel, *Akademik Boris Petrov* were deployed for the survey, location and recovery of the debris.

Location, search and recovery of the spacecraft debris from the sea are a costly endeavour that requires sophisticated technology and support data from ground control station. In the last couple of decades, recovery operations for similar rockets have been conducted in other parts of the world. Delta II launch vehicle which placed US satellite *Navstar 35* in October 1993, a vehicle similar to GSLV, re-entered the earth's atmosphere after 10 years. The body part of the rocket was recovered from Argentina[1]. Another Delta II launched on 10 November 2000 was recovered from Thailand (http://www.losangeles.af.mil/news/story.asp?id=123037637) in January 2005. Other recoveries are the Ariane 5, which fell into a swamp and space shuttle *Columbia* that fell on land and water. Recoveries of spacecraft rockets from the sea are rare. All the known recoveries from shallow water were accomplished manually by diving, whereas recoveries from deep waters, used remotely operated underwater vehicles (ROVs) and other similar vessels. The *Liberty Bell 7* capsule was recovered after 38 years by an ROV from a depth of 4500 m in the Atlantic Ocean; this is known to be the deepest recovery[2]. Similarly, the engine of H-II rocket flight no. 8 was recovered after two months of its launch, from 3000 m depth in the Ogasawara Sea[3], with the help of ROV *Kaiko* and ROV *Dolphin-K*. Debris from space shuttle *Challenger* was recovered from 370 m depth in the Atlantic Ocean[4]. A summary of the recovery of debris of spacecraft rocket is shown in Table 1.

The recovery of GSLV debris described in this communication was specifically aimed at L-40 engines that fell into 10–30 m depth, shallow waters of the Bay of Bengal.

All the engines of the GSLV had a lot of fuel, and disintegration of the launch vehicle and impacts of L-40 engines could be seen from SHAR at Sriharikota (Figure 1 *b* and *c*). The coordinates for impact points of four L-40 strap on engines ± 300 m were provided by ISRO. Location, search and recovery operations were carried out in three phases. Phase I – between 15 and 31 July 2006; phase II between 8 and 10 September 2006, and 20 and 27 September 2006, and phase III between 7 and 27 October 2006. After recovery of each engine, ISRO recorded the final locations, revising the preliminary locations given earlier. The initial and revised locations are given in Table 2.

Various platforms were used for the operations. Although bigger vessels ORV *Sagar Kanya* and *Akademik Boris Petrov*, were fully equipped for survey and recovery,

*For correspondence. (e-mail: ravimishra@ncaor.org)

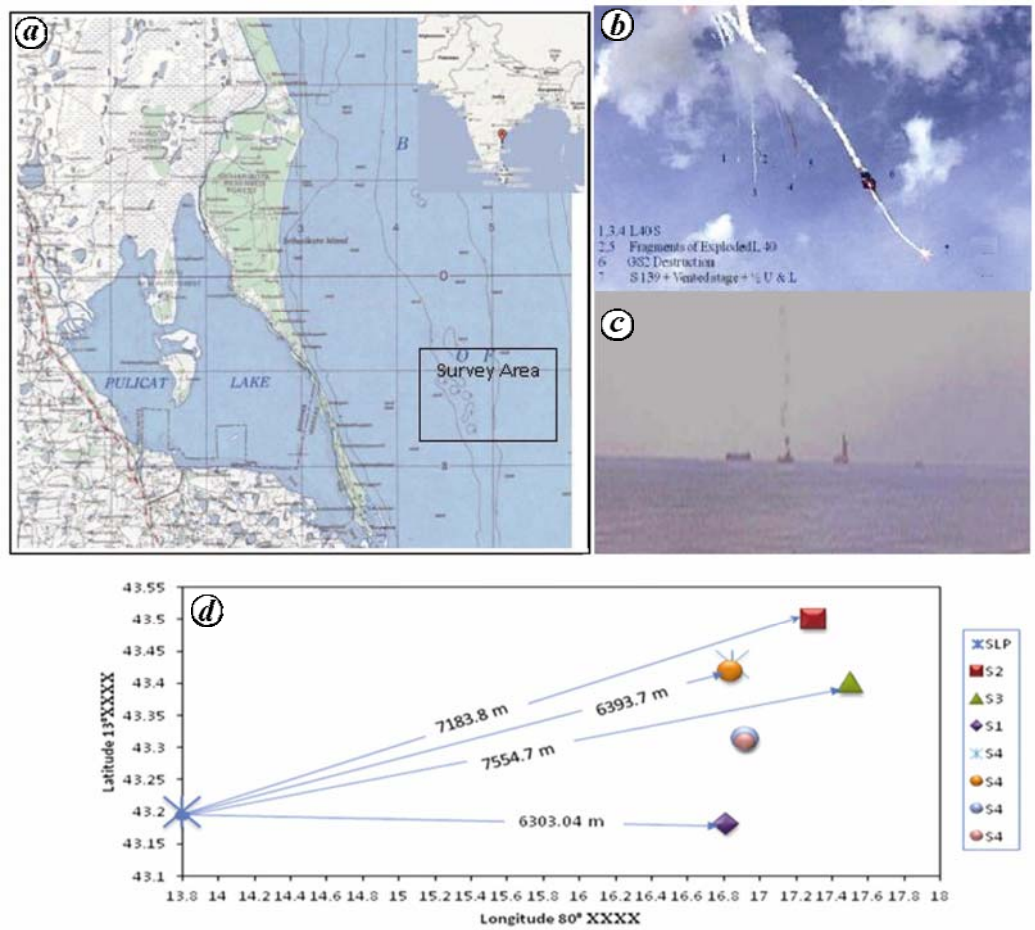

Figure 1. ***a***, Location map. ***b***, Disintegration and fall of Geosynchronous Satellite Launch Vehicle debris. ***c***, L-40 impact on the sea. ***d***, Relative position and distances of recovered L-40 engines from the launch pad (SLP).

they could not be used for survey in the present operation due to problems associated with shallow water depths. However, they were used for facilitating surveys, diving, accommodation and recovery of debris. All these four vessels were utilized in phase I of the operation, whereas in phase II only *Sagar Purvi* and *Sagar Paschimi* were deployed. *Sagar Paschimi* and *Akademik Boris Petrov* were utilized in phase III. In addition to these vessels, two fishing boats and survey boats of *Akademik Boris Petrov* were also utilized. The following operations were carried out: Multibeam bathymetric survey; side scan sonar survey; underwater videography; search by ROV; analysis of data and identification of target/location; fixing markers (setting up floats) on the sea surface for diving; diving for locating the debris, and recovery of the debris.

During phase I, all operations were carried out in a sequence. Diving was undertaken following surveying in phase II, whereas it was taken up while surveying was in the final stages in phase III.

Multi-instrumental approach was adopted in this operation to reduce the number of false targets for diving and recovery. Survey details, equipments used and survey platforms are given in Table 3.

Multibeam swath bathymetric survey: Because the seabed in the area is at a shallow depth of 10–30 m, EM 1002 and wide swath bathymetric system – Geoacoustic-Geoswath Plus, were deployed to find the target areas. In phase I, swath bathymetric survey was carried out using *Sagar Paschimi* between 16–18 July 2006 and 25–26 July 2006, covering an area of 16.20 sq. km. In phase III, survey over an area of 78 sq. km was completed between 8 and 13 October 2006. Closer to the shore, where depth to seabed is less than 10 m deep, the bathymetric system was fitted onto 7.9×2 m fibreglass survey boats of *Akademik Boris Petrov*, and data were acquired along 18 line km over an area of 3.24 sq. km. Targets identified are shown in Figure 2 *a* and *b*.

Side scan sonar survey: This has been used extensively in the search of spacecraft debris all over the world[5,6]. In the case of GSLV, they have been carried out in all the three phases of operations. EdgeTech DF 1000 and EdgeTech 4200FS side scan sonars were used. The survey was conducted between 18 and 20 July 2006 during phase I; between 9 and 11 September 2006 in phase II, between 8 and 13 October 2006 in phase III. During phase I, data were collected along 97.2 line km in an area

Table 1. Summary of the recovery of the some known spacecraft/rocket debris

Spacecraft/ rocket	Date of launch	Time of incident	Search area	Equipment used	Water depth (m)	Recoveries	Completion of operation	Remarks
Liberty Bell 7	21 July 1961	15 min 37 s after launching during reentry	Atlantic Ocean, 62 sq. km	Side scan sonar, ROV, high definition cameras	4500	*Liberty Bell 7* capsule	20 July 1999, after 38 years	Total 14 years of efforts for recovery
Space shuttle *Challenger*	28 January 1986	73 s	Atlantic Ocean, off the coast of central Florida, 1600 sq. km	Side scan sonar, divers, ROV, manned submersible	Up to 370	Crew compartment, solid rocket booster	1 May 1986, after three months; some shallow-water recoveries continued	After 11 years in 1996, two large pieces of the shuttle were recovered from Cocoa Beach
H-II Rocket	15 November 1999	4 min	Ogasawara sea, 86 sq. km	Side scan sonar, ROV, deep towed camera	3000	Main engine	24 December 1999	ROV *Kaiko* and ROV *Dolphin-3K* were used for recovery
Delta II	10 November 2000	13 January 2005, reentered the atmosphere	Land, Thailand		Land	Engine	13 January 2005	–
Delta II (*Navstar 35*)	26 October 1993	20 January 2004, reentered the atmosphere	Land, Argentina		Land	Rocket body of third-stage launch vehicle	20 January 2004	–
Ariane 5	4 June 1996	39 s	12 sq. km. land area close to the launch pad		Land	Solid propellant fragments, most elements of four-cluster satellite		More than 100 people over the period of several weeks and helicopter were used for recovery
Space shuttle *Columbia*	16 January 2003	1 February 2003, reentered into the earth's atmosphere	Land, Toledo Bend Reservoir, Lake Nacogdoches, California coast around 80 sq. km water bodies	Side scan sonar	12–20	Total 84,000 pieces, front gear, window frame, nose cone; only one piece from water	28 April 2003	30,000 people, over 1.5 million man hours, 37+ helicopters, 7+ aircraft, etc. were deployed for the recovery

Table 2. Impact points of L-40 engines and recovery of engines

Impact point/recovery	Latitude	Longitude	Remarks
A	13°43.4′N	80°17.2′E	Initial points
B	13°43.8′N	80°17.6′E	Initial points
C	13°42.8′N	80°17.5′E	Initial points
D	13°41.4′N	80°17.5′E	Initial points
New D	13°42.91′N	80°16.72′E	Point given after the recovery of S-2 and S-3 engines (completion of phase I)
E	13°42.91′N	80°18.44′E	Point given after the recovery of S-2 and S-3 engines (completion of phase I)
New E	13°43.03′N	80°18.60′E	Point given after the recovery of S-1 (completion of phase II)
S-3 engine (20 July 2006)	13°43.396′N	80°17.5′E	Recovered from the water depth of 12–14 m
S-2 engine (27 July 2006)	13°43.471′N	80°17.289′E	Recovered from the water depth of 12–13 m
S-1 engine (24 September 2006)	13°43.180′N	80°16.808′E	12–14 m
S-4 engines parts (14 October 2006)	13°43.4198′N	80°16.838′E	
S-4 base plate electronics (15 October 2006)	13°43.314′N	80°16.921′E	
S-4 shell plate (15 October 2006)	13°43.308′N	80°16.921′E	
S-4 nose cone (17 October 2006)	13°43.430′N	80°16.844′E	
Parts of engines and core vehicle (21 October 2006)	13°43.168′N	80°16.600′E	

Table 3. Survey details of the operational area during different phases

Date	Survey platform	Type of survey	Equipment	Latitude	Longitude	Area covered (sq. km)
Phase I						
16–18 July and 25–26 July 2006	CRV *Sagar Paschimi*	Swath bathymetry	Semrad EM 1002	13°41′–13°44′N	80°17′–80°18′E	16.20
19–22 July 2006	RV *Akademik Boris Petrov*	Swath bathymetry	Atlas Hydrosweep DS-2	Started in the beginning of the operation, but closed due to no coverage in shallow depth		
20–25 July 2006	Survey boat *Akademik Boris Petrov*	Swath bathymetric	Geoacoustics-Geoswath Plus System	13°43.0′N–13°44.0′N	80°16.5′–80°17.5′E	3.24
26–27 July and 27–30 July 2006	ORV *Sagar Kanya* RV *Boris Petrov*	ROV	Benthos MK-II ROVER	Limited operation due to limited coverage and poor visibility		
19–27 July 2006	ORV *Sagar Kanya*	Side scan sonar	Geoacoustics-SS982	Selected location close to the targets		
18–20 July 2006	CRV *Sagar Purvi*	Side scan sonar	EdgeTech DF 1000	13°41′–13°44′N	80°17.4′–80°18′E	9.72
Phase II (survey carried out around 500 m radius from the impact points D and E)						
9–11 September 2006	CRV *Sagar Purvi*	Side scan sonar	EdgeTech DF 1000	13′ 42.91′N	80°16.72′N	6
Phase III						
8–13 October 2006	CRV *Sagar Paschimi*	Swath bathymetric	EM 1002	13°41′–13°45′N	80°16′–80°23′E	77.76
8–13 October 2006	CRV *Sagar Paschimi*	Side Scan Sonar	EdgeTech 4200 FS	13°41′–13°45′N	80°16′–80°23′E	77.76

of 9.72 sq. km. In phase II, the survey was centred in an area of 500 m radius around points D and E. In phase III, data were collected along 561 line km in an area of 78 sq. km.

Remotely operated underwater vehicle: ROV-Benthos–MKII Rover was deployed from *Sagar Kanya* and *Akademik Boris Petrov* along pre-determined tracks passing close to the suspected objects reported from the surveys in phase I of the operations. In general, ROV was not useful due to poor visibility in the shallow waters of the area of interest.

Phase I surveys identified 27 locations. Eighteen more were identified in phase II. Search by a team of 10 professional divers commenced on 18 July 2006. Diving in the area was feasible from low platform vessels – *Sagar Purvi* and *Sagar Paschimi*. Survey boat of *Akademik Boris Petrov* also served as a good platform for diving. Differential GPS (DGPS) and Gyrocompass fitted with Geoswath bathymetric system were helpful to locate the diving positions and setting up of floats. Two small fishing boats were used for transport of supports for diving.

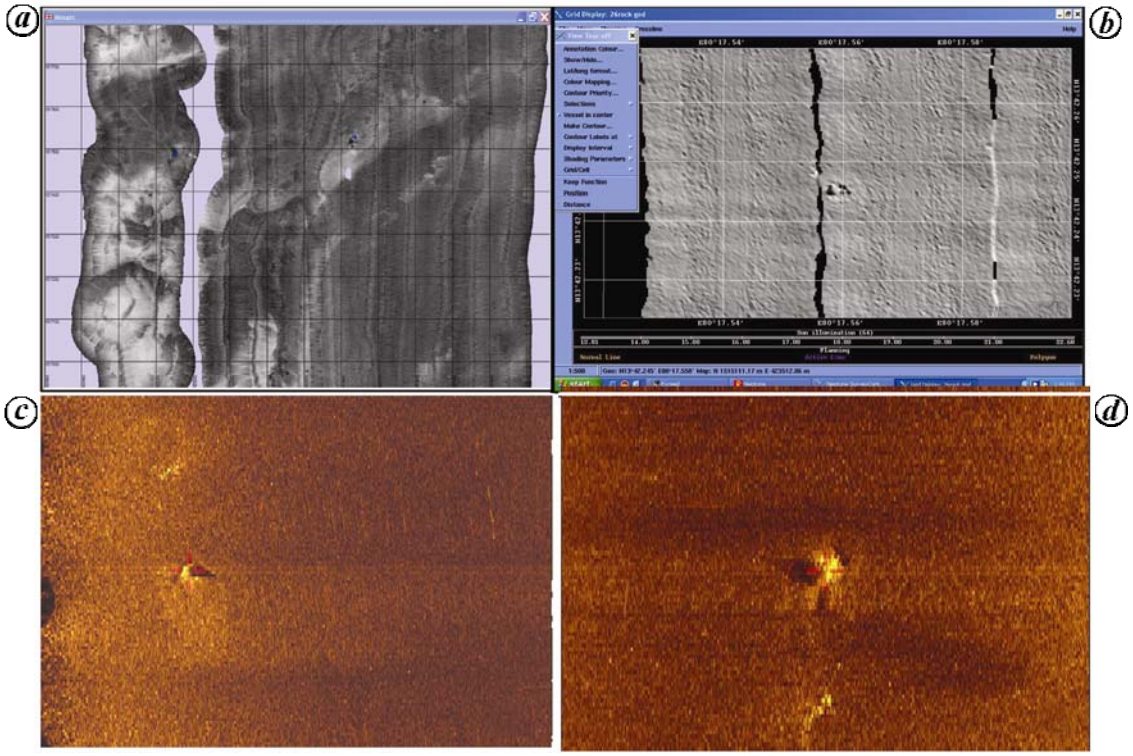

Figure 2. Identification of targets in bathymetric survey. ***a***, Geoswath survey. ***b***, EM1002 Survey. ***c***, ***d***, Sonar images of S-4 nose cone observed from different directions.

The diving team was divided into two groups. They carried out searches at two locations simultaneously.

All the 27 targets identified by surveys during phase I were verified by diving. Search operations were over a period of 6–8 h in an area of 150 m around each location. Location #18 was indicated by both swath bathymetric and side scan sonar surveys. Underwater videography confirmed the presence of engine and its parts near this location. Strap-on engine S-3 and its parts strewn around, were recovered near location #18 and loaded onto *Sagar Kanya*. Strap-on engine S-2 was recovered close to the impact site A. Search was continued for other strap-on engines during phase I operations till 31 July 2006.

The diving team was again mobilized on 19 September 2006 to search for the debris in the 18 locations identified by surveys in phase II. Search began on 21 September. Strap-on engine S-1 was recovered on 24 September, near the point that was designated as new E after recovery.

Phase III surveys that concluded on 13 October 2006 led to identification of 49 locations as possible target areas for debris of strap-on engine S-4. Search operations were taken up on 12 October itself, even while the surveying was in progress. The engine had disintegrated and its parts including nose cone, that were scattered were recovered by the search team in an area of about 200 m radius. After the recovery of parts of S-4, the search operations were concluded on 21 October 2006.

In summary, search and recovery of GSLV parts was accomplished in about 100 days from the date of mishap. Three strap-on engines S-1, S-2 and S-3 (Figure 3 *a–c*), and parts of engine S-4 and its nose cone were recovered (Figure 3 *d–f*). Engines S-2 and S-1 were located within a radius of a kilometre of the predicted impact points. Engine S-1 and its parts were scattered in about 0.5 sq. km area. Components of engine S-4 (nose cone, middle parts of the stage and base plate electronics system) were recovered from a number of locations (Figure 1 *d*). Molten, twisted and broken metallic pieces of the lower stage of S-4 were strewn in an area of about 1 km around the place where the S-4 nose cone was recovered. Non-recovery of the S-4 engine, and scattering of its parts at different locations, point to total disintegration of the engine.

Recovery of spacecraft debris is rare compared to that of aircraft. Search for black box of aircraft is facilitated by sound-emitting devices[5,6]. In the case of spacecraft, most of flight-related data are available from ground control stations. Therefore, search for spacecraft debris is more challenging, especially if it is in water bodies. For example, the debris of Ariane 5 of the European Space Agency, which failed on 4 June 1996 at a height of 3.7 km, was scattered over an area of 12 sq. km in a mangrove swamp and savannah close to the launch pad[7,8].

Unlike Ariane 5, the GSLV debris had to be recovered from shallow waters of the Bay of Bengal. Shallow-water regions of the sea are associated with many practical problems, such as poor visibility, influence of the coastal water flow, heavy water currents, difficult navigation and towing conditions. In the area where GSLV fell,

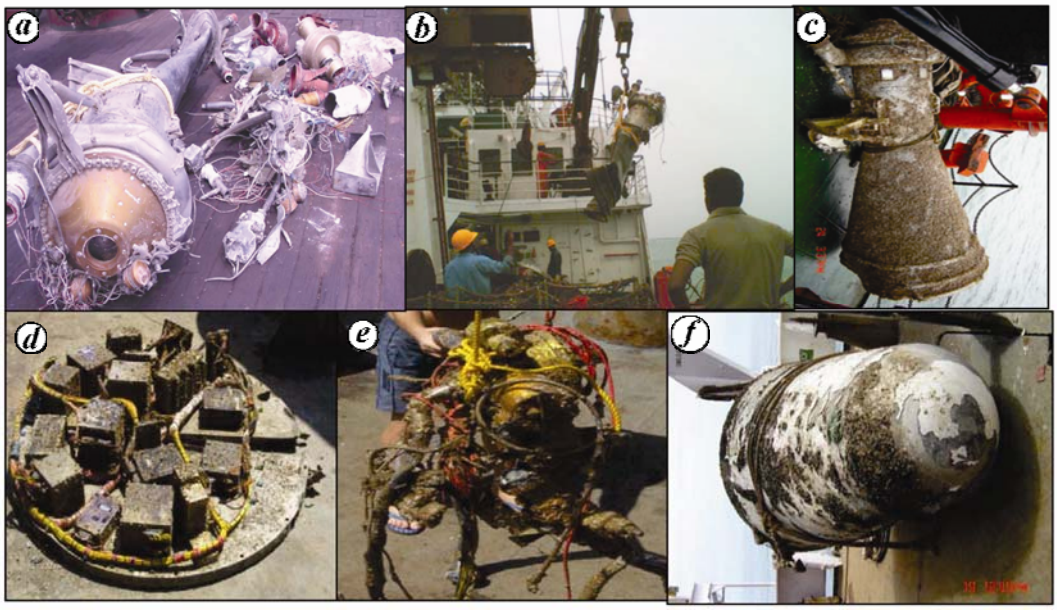

Figure 3. Photograph of recovered engines and their parts. ***a***, S-3 engine; ***b***, S-2 engine; ***c***, S-1 engine; ***d***, S-4 base electronics plate; ***e***, S-4 engine parts and ***f***, S-4 nose cone.

underwater visibility was generally about 1 m, and less than 30 cm on some days. Further, in shallow waters, sonar images show false targets which are associated with many natural features. In the present case, a number of submerged sand bars, sand ridges, ripples on the seafloor and undulations up to a metre height were observed. In the case of GSLV recovery operations, approximately 300 targets were identified by the sonar survey in different directions along different paths (Figure 2 *c* and *d*). On comparing these with the results from swath bathymetric surveys, the potential targets were reduced by 70%, and only 94 targets were chosen for search and recovery. Thus careful surveys could limit the diving operations. These are few compared to 3100 potential targets in Toledo Bend and 326 targets in Lake Nacogdoches, which were found by sonar survey during the search for debris of space shuttle *Columbia*[9].

Therefore, locating and recovering GSLV debris may be considered as a satisfying and successful operation from the shallow sea. The success can be appreciated, if one compares the present operation with the story of recovery of parts of space shuttle *Columbia*. Only one piece of the shuttle was recovered from a lake and none from the California coast. In the case of *Challenger*, searches continued even after initial major search operations, and 11 years after the event, on 17 December 1996, two large pieces of the shuttle were recovered in the shallow waters of the Cocoa Beach, Florida[10]. GSLV recovery operations underscore the importance of multi-instrumental approach in search operations under shallow sea settings.

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