A hybrid 3D sensor (NEPTEC TriDAR) for object tracking and inspection

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ABSTRACT

Although laser ranging and scanning sensors are widely used in a variety of industries, a sensor designed for spacecraft operations, including autonomous rendezvous, inspection and servicing remains a challenge. This is primarily due to critical requirements, including the need to have simultaneous high sampling speed, and good range and lateral resolution at both short range of a few meters and at long range of a few hundred meters.

A typical LIDAR sensor is not suitable for tracking at the close-in distance, just before rendezvous, or during a critical close-up inspection, since its range resolution is in the tens of millimeters and can only be improved by averaging at the expense of speed. A laser triangulation sensor is capable of simultaneously having both high range resolution (~1mm) and high speed (~10kHz) at short distance. But the range resolution of a triangulation sensor reduces rapidly as range increases, its performance is inferior compared to a LIDAR based sensor at long range.

NEPTEC TriDAR (triangulation + LIDAR) is a hybrid sensor that combines a triangulation sensor and a TOF sensor for spacecraft autonomous rendezvous and inspection. It has been developed in part from technology used in NEPTEC's OBSS (Orbiter Boom Sensor System) 3D laser camera. The OBSS LCS was used for inspection of the Shuttle tiles on STS-114. In this paper, the TriDAR design that combines triangulation and LIDAR to produce high speed and high resolution for both short and long range is described. To successfully produce this sensor for space, an athermalized optical steering system shared by the two sensors has been developed. Results from performance testing of a prototype, designed for autonomous rendezvous, are given.

Keywords: autonomous rendezvous, tracking, triangulation, LIDAR, 3D, inspection, time-of-flight.

1. INTRODUCTION

A 3D ranging and imaging sensor has important applications in space exploration, notably autonomous rendezvous, inspection and satellite servicing. Autonomous rendezvous is identified by NASA as a critical step for the upcoming Lunar and Mars mission. According to NASA, the ability to rendezvous and dock with no or minimum human input is considered as an integrated part of CEV (crew exploration vehicle), which is a collection of human and robotic space systems that will allow astronauts to travel safely and cost-effectively to the Moon and Mars. Servicing of satellites on-orbit also requires the ability to rendezvous and dock autonomously by an unmanned spacecraft. Initially a robotic mission was planned for repair of the Hubble Space Telescope. Autonomous rendezvous and docking was identified as the most critical activity during that mission.

Currently, Russia has unmanned docking capability with its Progress spacecraft. The European Space Agency is developing unmanned docking capability for its new Automated Transfer Vehicle. NASA has tested DART (Demonstration for Autonomous Rendezvous Technology), but much development has to be completed before a highly reliable and safe automated system is operated in space.

During a typical docking operation, there are different requirements depending on the target distance, and there are also different methods to extract the information about a target. At a range of about a kilometer, only the bearing and position of the target is required to determine blob detection. At a range of about a hundred meters, the pose of the target is measured based on the shape of the target. At a range of about a meter, the pose of the target is measured based on local features on the target, e.g. features of a docking port. Advance of sensor technologies and novel tracking algorithms has

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led to a few new approaches of autonomous rendezvous and dock, but it still typically requires multiple systems to complete the operation. It is desirable to have one system that can do the tracking at all distances.

The systems can also be cataloged into two groups, the first group needs pre-installed objects on the target such as retro-reflectors, and the second group does not. The systems in the first group have easily detectable signals and a fast data processing rate, but they have a limitation on the target side. Some targets, like the Hubble Space Telescope, do not have the necessary tracking objects and they can not be docked by these systems. The position and orientation of the tracking objects must be meticulously maintained during the manufacturing process, which is not an easy task considering there are normally many instruments from different contractors on a typical space mission. There are also risks of mission failure due to the damage of these pre-installed tracking objects. The systems in the second group put more stringent requirements on tracking sensors and software, but they are more flexible and have wide applications, they are the focus of the new generation of tracking systems.

LIDAR based sensors have gained popularity over RADAR based sensors because of their superior resolution, they also have the advantage of long detection distance and immunity to ambient light over stereo-camera based systems. The most mature and widely used LIDAR technology in space operation is pulse laser based TOF (time-of-flight) LIDAR. In this paper, LIDAR is only discussed in the framework of pulsed laser based time of flight LIDAR.

NEPTEC TriDAR is a hybrid sensor that combines a triangulation sensor and a LIDAR sensor. It uses LIDAR to do blob detection at long distance, pose estimation at distances out to 200m, and it uses a triangulation sensor to do pose estimation at short distances. Pose estimation at short distances intrinsically requires that the sensor acquire high resolution 3D images to allow the sensor to be used for close-up inspection of the target. In fact, the TriDAR has been developed in part from technology used in NEPTEC's OBSS (Orbiter Boom Sensor System) 3D laser camera that was used for inspection of the Shuttle tiles on STS-114. [1] In this paper, the design of the prototype TriDAR sensor is described and test results are reported and discussed.

2. NEPTEC TriDAR SENSOR

2.1 Complementary Nature of a LIDAR and a Triangulation Sensor

Active triangulation with a pointing laser is a well-known technique for measuring distance. Figure 1 shows the basic scheme of a 1D triangulation system. A laser beam is projected onto a target, a spot on the target is imaged by a lens onto a CCD detector array. When the target moves in the range direction, the corresponding spot image moves along the array. By reading the peak position on the detector array, the range profile of an object is determined. A triangulation sensor can have a range resolution in sub-millimeter within 2m and measure about 20k voxels per second. Since the triangulation uses angle to measure range, its range resolution $\boldsymbol{\Delta R}$ is proportional to range square $\boldsymbol{R^2}$, i.e. its range resolution decreases rapidly when the range increases.

A pulse laser based LIDAR on the other hand, can have a range up to several kilometers with a speed of 10k voxels per second and a resolution on the order of 1cm. Its range resolution is determined by the jitter of timing electronics and is close to constant regardless of the range. LIDAR range resolution can be improved by averaging out the timing jitter noise, but the improvement is obtained at the expense of speed. In terms of range and range resolution, LIDAR and triangulation are complementary to each other. [2] Optically, a triangulation sensor and a LIDAR can be combined together by using dichroic filters as shown in Neptecs patent pending TriDAR optical arrangement, Figure 2.

2.2 Neptec TriDAR Optical Arrangement

Neptec's triangulation sensor is based on an autosynchronous method as shown Figure 3. [3] It uses a near infrared continuous wave (CW) laser, the projection beam is steered by an X mirror and a Y mirror, the mirrors are driven by two (orthogonal) galvanometers. The return beam is collected by a telescope and projected onto a high-density detector array. The basic idea of autosynchronization is to sweep the laser and the detector array simultaneously, in order to measure a 3D object without physically moving the sensor or the object. The location of the return beam spot on the detector array and the driving mirror angles is used to determine the location of the object. The benefit is that the instantaneous field-of-view of the detector is very small, which reduces noise from background light.

A near infrared pulse laser is used in the LIDAR arrangement. The collimated LIDAR beam is incorporated into the scanning optics by using a pair of dichroic filters as shown in Figure 2. The first dichroic filter combines the LIDAR beam with the triangulation beam into the scanning optics. The second dichroic filter splits the returned LIDAR signal into the LIDAR receiver. By using common scanning optics, the TriDAR design takes full advantage of both triangulation and LIDAR while maintaining a smaller footprint, lower power and simpler system design compared to using two separate sensors.

Using a dichroic filter has the benefit of combining or splitting laser beams without the loss associated with standard beam splitters. In addition, it provides a convenient way to optimize spot size either at short distance or at long distance. For example, in order to have good lateral resolution of the triangulation sensor at short distance, its minimum spot size 2ω (diameter at $1/e^2$) is desired to be 1mm or less. According to Gaussian optics, the beam divergence θ is given by:

$$\theta = \frac{\lambda}{\pi} \cdot \frac{1}{\omega} = 9.6 \times 10^{-4} (radian)$$

At 200 meters, this beam divergence will produce a spot size with a diameter of 0.4 meter, which could be inadequate for extracting the pose information from the shape of a docking target. If two beams are used, the second beam for LIDAR has a larger size at the exit and a smaller beam divergence, producing a smaller spot size at 200m. Therefore the approach of using dichroic filters allows TriDAR to use two beams with different sizes to achieve high lateral resolution in both short distance and long distance.

2.3 Athermalized Design of Optical Platform

TriDAR is designed for space applications. Therefore, it must withstand the extreme temperature swings (-40°C to 80°C) in space and the launching/landing vibration spectrum. The material used in the design must have desirable features including low coefficient of thermal expansion (CTE), high stiffness to weight ratio, low outgassing as well as acceptability under NASA material selection standards. Neptec has designed an athermalized platform to support and house the optics. [4] It was first tested as a DTO (development test objective) on the Shuttle Discovery during Mission STS-105 to the International Space Station in August 2001, and it was later used by NEPTEC's LCS 3D laser camera to inspect the Shuttle tiles during Mission STS-114 in July 2005. Figure 4 shows a CAD model of the Neptec prototype TriDAR optical assembly and enclosure base. The optical base plate and mirror mounting arrangement are the most critical parts in the opto-mechanical design.

The optics base plate is the foundation of the TriDAR optics, it is made from a panel of quasi-isotropic $[0/45/90/135]_{sn}$ graphite/cyanate ester (K13710/CE3) manufactured by COI Materials. The panel is composed of 48 plies of 0.13mm (5mil) prepreg and consolidated at an autoclave cure cycle of 180°C, 690kPa and 101.3kPa of vacuum. An EMI shield of 0.08mm (3mil) 1145-0 aluminum foil is co-cured to the underside of the panel using BR127 primer adhesive. The base plate is cut from the center of the panel and the final base plate thickness is 5.6mm with a ground and lapped surface flatness of 0.025mm.

In the design, the size of the Y-axis mirror is dominated by the resolution requirement of the triangulation. A longer mirror can provide a larger triangulation angle and a better resolution. But a large mirror poses design challenges due to the inertial limitation of the driving galvanometers, the torsional deflection of the mirror at high turning speeds, the optical surface quality, the shuttle launch/landing vibration spectrum and NASA material approval. The TriDAR Y-mirror is designed using high strength beryllium and a stiffening backbone. The design achieves an inertia of 25 $gm \bullet cm^2$ and a negligible angle of twist. To ensure survival during the launch/landing vibration spectrum, the optical components are designed to have a resonant frequency above the maximum frequency encountered during shuttle launch/landing. By incorporating a secondary bearing support into the design of the Y-axis mirror mount, the first mode undamped frequency of the Y-axis mirror is driven above 2000Hz.

The enclosure design, Figure 4, provides for both active and passive thermal control through the use of foil heaters, conduction surfaces and reflective external surfaces. The optical base plate, mirrors and mirror mounts are designed to minimize thermal distortion over a temperature range 0°C to +50°C and minimize deflection during launch vibration.

Design of the components was achieved using Pro/ENGINEER solid modeling software. Structural and thermal analysis was accomplished using COSMOS/M, Thermal Desktop and RadCAD finite element software.

3. RESULTS FROM A TriDAR AND DISCUSSIONS

A prototype TriDAR system was assembled and used to evaluate the parameters listed below.

- Launching system efficiency.
- Range measurement.
- Optimized spot size.
- Field of view.
- Resolution in both lateral and range directions.
- Collection system efficiency.
- Returned signal versus target materials.
- Interference between channels of LIDAR and triangulation.
- Effect of internal stray light and solar background.

The triangulation sensor measures objects at short range. Its near infrared CW laser has a power of 100mW, with spot size of less than 6mm within the short range. The minimum spot size at beam waist is less than 2mm at short range. The range resolution is 0.3mm at 1m and increases to 12mm at 10m. The lateral resolution is one quarter to one half of its spot size for the Gaussian beam, which is less than 3mm within a 10m range. The triangulation sensor can acquire up to 10k voxels per second and has a field-of-view of 30°x30°.

The LIDAR used in the prototype was a modified commercial unit. It measures objects ranging from short range to greater than 200m. The LIDAR has a near infrared pulse laser with a peak power of 65W and a spot size of 25mm at the exit of the unit, with a beam divergence of 7mrad. The range resolution is 25mm, and the lateral resolution is approximately one-half of its spot size, since its beam has a flat-top power distribution. The range resolution can be improved by return signal averaging at expense of the sampling rate. The LIDAR system can also acquire up to 10k voxels per second and has a field-of-view of 30°x30°.

Figure 5 shows the test up for tracking study of a $1/10^{th}$ scale model of the Hubble Space Telescope. The mockup contains a large cylinder with two rectangular solar panels extending from each side. The bottom part of the mockup is covered with silver Teflon tape and the top part is covered with aluminum foil.

During the test, the model was installed on a test rig that allowed full 360 degree rotation about one axis and translation up to 7 m. When the model was moved on the rail, it was rotated 360 degrees about its *z* axis (yaw motion) at various ranges in order to assess the sensitivity of the tracking algorithm to the shape of the model. The pose estimation was measured at a rate of 1 to 5 Hz and pose error was measured at each range and for each rotation angle increment of 15 degrees. The pose estimation accuracy was less than 1cm in translation and less than 1º of rotation, the details of the performance of pose estimation are discussed in reference 5.

The Hubble Space Telescope is a good representation of typical space objects, they are normally covered by highly reflective materials and have a cylindrical shape. This combination poses a stringent requirement on pose estimation for LIDAR, since most of the light on the edge of the target is reflected away from the LIDAR receiver. The estimate of the maximum pose range of the prototype TriDAR was 75m, with blob detection 150-200m.

From the results of TriDAR testing, it was determined that the most critical improvement for the TriDAR design is to increase the laser power and reduce the beam divergence. These modifications will provide accurate pose estimation of reflective surfaces out to a range of 200m and blob detection to 1km.

The commercial LIDAR uses an InGaAs based pulse laser. The advantage of using a semiconductor pulse laser is its small size, low power requirement and high reliability. InGaAs is also considered to be a radiation hardy material. The LIDAR unit was tested under the required radiation dose and was found to have no issues regarding the laser source. The disadvantages of using pulse lasers are low power and large beam divergence. NEPTEC is working with INO (National Optics Institute) to design a novel pulse source that can deliver the required higher pulse power and low beam divergence.

4. SUMMARY

A prototype TriDAR has been built and was used to successfully demonstrate sharing of beam steering optics between triangulation and LIDAR, synchronization of a LIDAR signal with the DTO LCS electronics, and the best methods of optical alignment. The design utilizes dichroic filters to split the emitted and return signals from a CW and LIDAR laser source.

The TriDAR space design incorporates materials with low coefficient of thermal expansion and high strength to weight ratio to survive the severe thermal environment of space and the launch/landing vibration spectrum. Athermalization is achieved through conductive cooling of the electronics using thermal planes, an aluminum enclosure, and reflective exterior surfaces.

In summary, Neptec TriDAR is a 3D sensor designed for space autonomous rendezvous and inspection. The design utilizes the technology used in NEPTEC's space-qualified OBSS 3D camera, for short distance measurement, and incorporates a LIDAR sensor for long distance measurement. By combining the advantages of a triangulation sensor and a LIDAR sensor, the TriDAR offers high resolution in both range and lateral directions, and high sampling speed at all ranges. While TriDAR retains the capability of inspection at short distance, as demonstrated with the OBSS LCS in the 2005 flight of Shuttle Discovery, test results of the prototype TriDAR demonstrate the potential of TriDAR as a sensor that can meet all requirements in the three stages of autonomous rendezvous and docking. The next generation TriDAR is being constructed at Neptec with much improved long range LIDAR capability.

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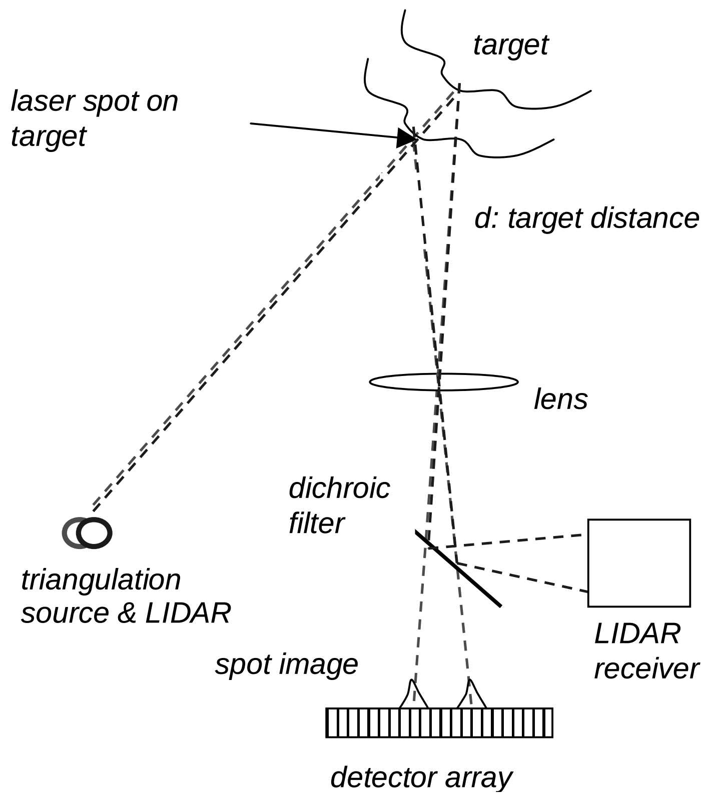


Figure 1: Scheme of an active triangulation sensor and a LIDAR

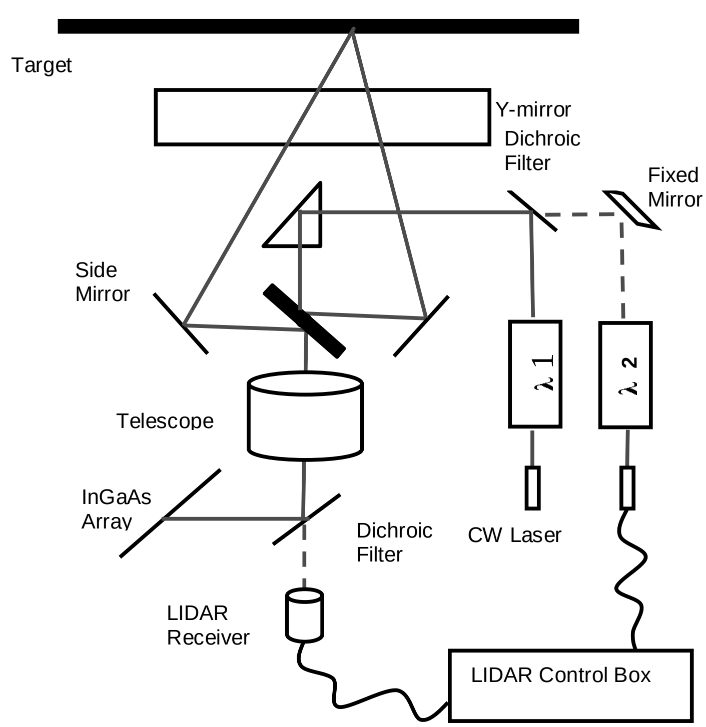
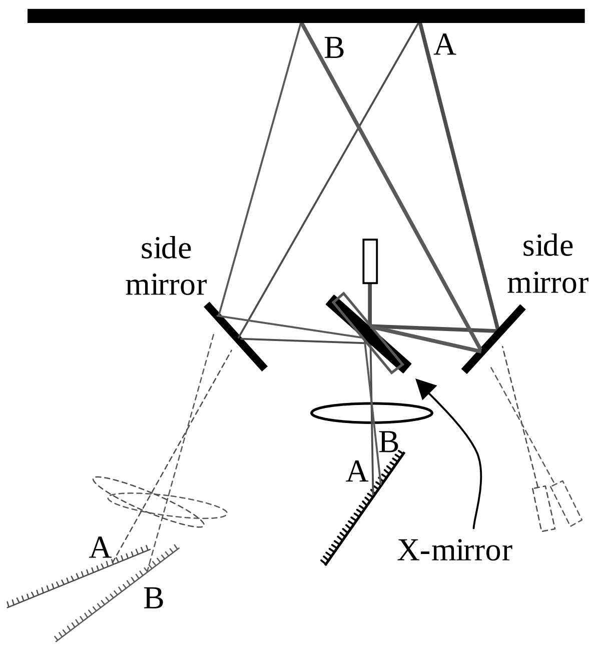


Figure 2: TriDAR optical arrangement



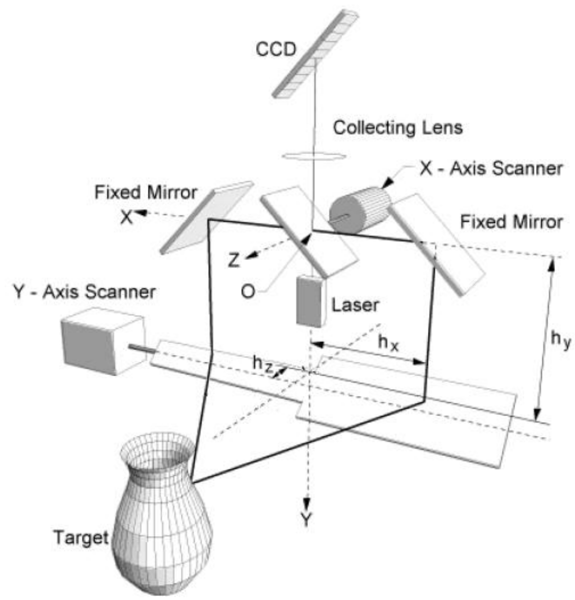


Figure 3: Autosynchronous triangulation used in DTO LCS

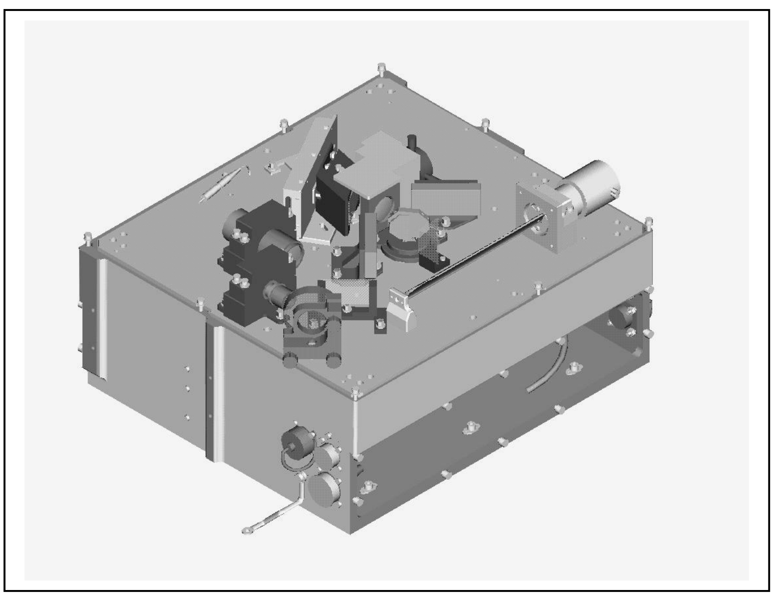


Figure 4: CAD model of Neptec prototype TriDAR

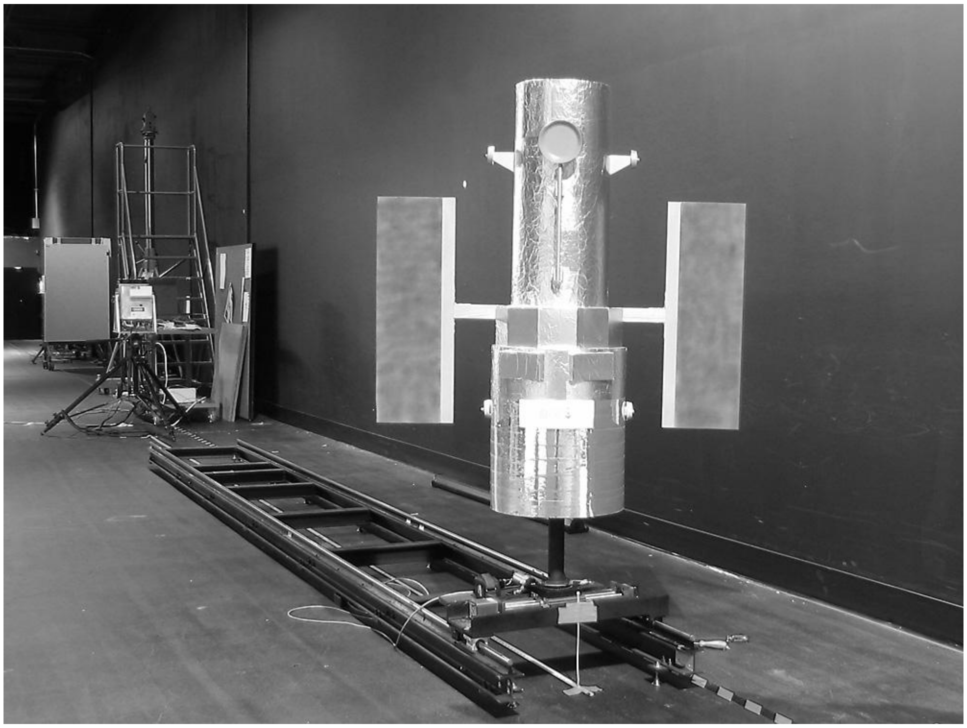


Figure 5: Test setup of the TriDAR with 1/10th scale Hubble model