

## **OWL-Net: Global Network of Robotic Telescopes for Satellites Observation\***

**Jang-Hyun Park<sup>(1)</sup>, Hong-Suh Yim<sup>(1)</sup>, Young-Jun Choi<sup>(1, 2)</sup>, Jung Hyun Jo<sup>(1, 2)</sup>, Hong-Kyu Moon<sup>(1)</sup>, Young-Sik Park<sup>(1)</sup>, Dong-Goo Roh<sup>(1)</sup>, Sungki Cho<sup>(1)</sup>, Eun-Jung Choi<sup>(1)</sup>, Myung-Jin Kim<sup>(1)</sup>, Jin Choi<sup>(1, 2)</sup>**

*(1) Korea Astronomy and Space Science Institute, 776, Daedeokdae-ro, Youseong-gu, Daejeon, Republic of Korea*

*(2) University of Science and Technology, Daejeon, Republic of Korea*

### **ABSTRACT**

The OWL-Net (Optical Wide-field patrol Network) is composed of 0.5m wide-field optical telescopes spread over the globe (Mongolia, Morocco, Israel, South Korea, and USA). All the observing stations are identical, operated in a fully robotic manner, and controlled by the headquarters located in Daejeon, Korea. The main objective of the OWL-Net is to get orbital information of Korean LEO and GEO satellites using purely optical means and to maintain their orbital elements. The test-phase operation of the whole system started in early 2017. Some test results and analysis for system performance will be presented, and their implications will be discussed.

### **1. Introduction**

Tracking of LEO satellites using an optical system is clearly disadvantageous compared to a radar system, but it is within a reasonable range of cost and technology for most users. Several types of optical surveillance systems have been developed since the Baker-Nunn camera, one of the earliest optical system to monitor satellites ([1], [2]). Even though tracking of LEO satellites is mostly resorted to radar systems, the use of optical systems to determine orbits of GEO satellites is still increasing. In recent years, most of the technical components for optical surveillance such as optics, mechanics, electronic control, and detector have been remarkably improved compared to the Baker-Nunn camera era. If we are not interested in monitoring tens of thousands of space objects but dozens of space objects, optical tracking and monitoring can be a cost-effective alternative.

The OWL-Net is a system developed to track LEO satellites at a relatively low cost using current technology for optical observation and to determine orbit by analyzing optical data. It is designed as a multipurpose system capable of observing GEO satellites as well as LEO satellites and performing astronomical observations. It is currently operating in five countries over the world, including Korea. Following sections describe OWL-Net sites, system configuration, operation, observation modes, and some early results, respectively. Some system-wide topics are discussed in section 7.

### **2. OWL-Net Sites**

The OWL-Net consists of one headquarters located in the KASI campus and five identical observatories spread over the world. We analyzed the basic conditions (weather conditions, infrastructure, maintenance support, accessibility) of over 300 astronomical observatories around the world and selected 17 sites as feasible candidates for the OWL-Net sites. Finally, five sites were selected after additional investigations and direct visits. The final five sites are located in Mongolia, Morocco, Israel, the United States, and Korea (Fig. 1). We tried to find sites in the southern hemisphere because some southern sites could see LEO satellites when they are not visible in the northern hemisphere, but failed. We tried to distribute the sites as evenly as possible over the longitude grid.

\*This proceeding paper is a summarized version of the paper published in *Advances in Space Research*, Volume 62, July 2018 (<https://doi.org/10.1016/j.asr.2018.04.008>).

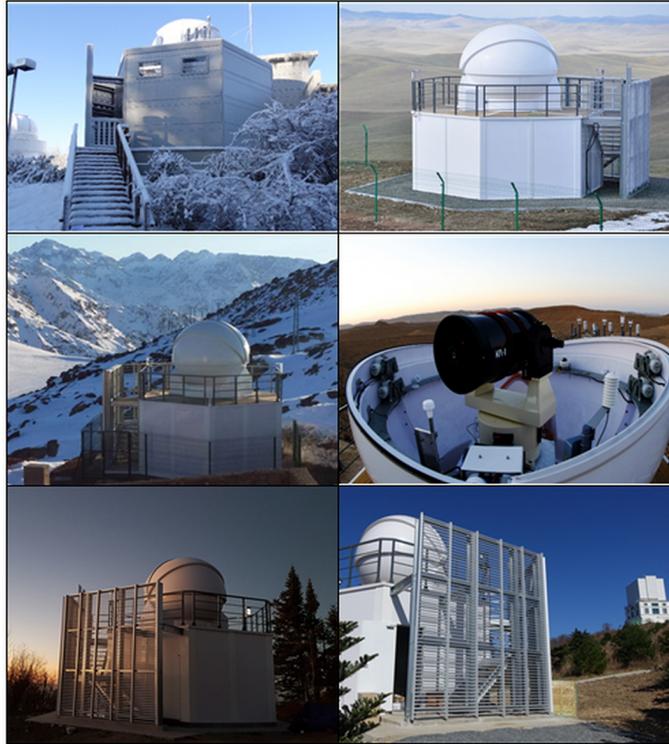


Figure 1. Site photos of the OWL-Net (Testbed, Mongolia, Israel, Korea, USA, and Morocco counter clockwise from the upper left)

Colored lines in Fig. 2 are GEO belt elevation angle at each site, and centered lines are GEO belt coverage when the elevation angle is greater than 20 degrees. The color code is the same as that of each site color. The OWL-Net can see most of the GEO belt, except for a very narrow slot near the west end. However, if we allow slightly lower elevation angle, we can expect full coverage.

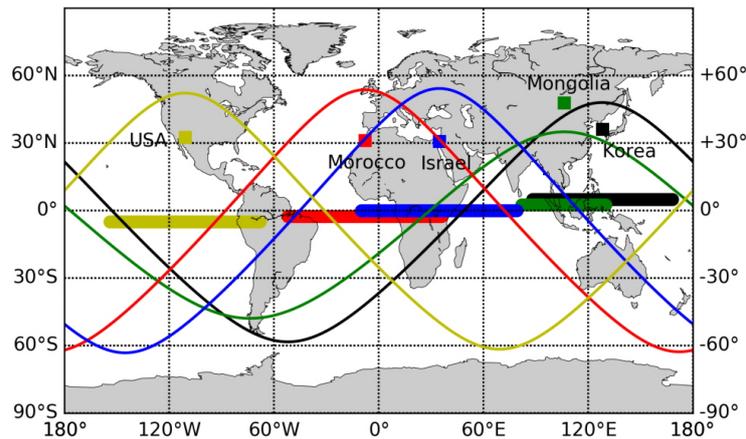


Figure 2. Site location map (colored squares) of the OWL-Net. GEO belt elevation (colored lines) angle and coverage (centered lines) are also showed when the elevation angle is greater than 20 degrees. The color code is the same as the square colors. The OWL-Net can see most of the GEO belt except very narrow slot around 173° N.

### 3. OWL-Net System Configuration

Fig. 3 shows the final configuration of the OWL-Net. Each observatory is based on an optical wide-field telescope. The network operating system in the HQ controls the whole network. Each observatory is controlled by a site operating system. Every observation is performed by a pre-determined schedule in an autonomous style. For robustness, we have adopted custom-made designs for most components and heavy duty environment monitoring systems. Performance goals of the OWL-Net at the system level are  $\sim 5$  arcsec and  $\sim 10$ km on satellite tracking and orbit determination accuracy, respectively. But, we expect better orbit determination accuracy than this number.

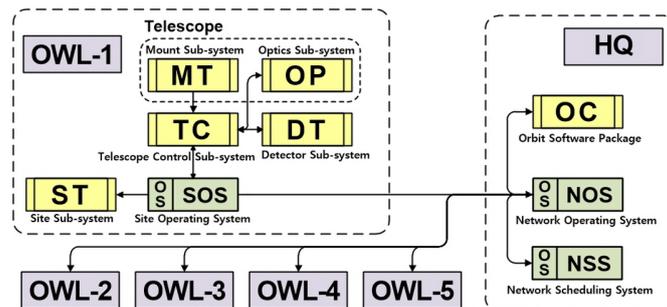


Figure 3. System configuration of the OWL-Net. The OWL-Net consists of five identical optical observatories and a headquarters.

We developed a telescope system (optical tube assembly, mount, and telescope controller) optimized for satellite tracking. The aperture size of the mirror is 0.5 m. The mirror is in the Ritchey-Chretien configuration, and its field of view is  $1.1 \text{ deg} \times 1.1 \text{ deg}$  on the CCD sensor. The optical tube assembly was manufactured by Officina Stellare, an Italian vendor. The alt-az type telescope mount was developed exclusively for the OWL-Net. The telescope has a maximum slewing speed of  $20 \text{ deg/sec}$ , and its acceleration performance is  $2 \text{ deg/sec}^2$ . The telescope has a pointing accuracy is  $\sim 3$  arcs, and its tracking accuracy is  $\sim 2$  arcs/10 minutes. The de-rotator was adopted to compensate the alt-az type motion. A clamshell type dome was developed to cover the telescope. Its structure is relatively simple and its sight is quite wide.

We also developed dedicated control electronics and software for the OWL-Net telescope system because frequent upgrades or discontinuity of commercial electronics makes maintenance difficult. The telescope control electronics are installed directly inside the mount and controlled via an internet connection. Because the telescope is exposed to extremely low temperature during the winter time, a heater is installed to control the temperature around the electronics.

The OWL-Net system uses electrically cooled  $4k \times 4k$  CCD cameras from FLI. The pixel size is  $9 \mu\text{m}$ , and the plate scale is  $\sim 1$  arcsec. Johnson B, V, R, and I filters are inserted in the filter wheel. We typically use the R filter for satellite observation. Recently, we are testing some clear filters for more light.

For easy replacement and maintenance of instruments, we designed a single unit back-end including the CCD camera, called the "wheel station". The wheel station includes all moving parts such as the filter wheel, the chopper, and the de-rotator. We adopted a chopper system to obtain multiple streaks from a single exposure. The rotation speed of the chopper can be varied up to 50 Hz. A time tagger is placed in the wheel station. It records time intervals between adjacent changes of chopper blade position and its time accuracy is  $\sim 1$  millisecond.

For robotic observation, we need a robust environment monitoring platform. The environment monitoring system is composed of one automatic weather station, three sets of temperature and humidity sensors, three sets of wind speed and direction sensors, one cloud sensor, and two CCTVs. For monitoring the inside of the dome, another set of temperature and humidity sensors and one CCTV are also installed. All the data from the monitoring system are collected to a dedicated processing board and then transferred to the HQ. Fig. 4 shows environment monitoring systems installed at the site in Wise Observatory, Israel.



Figure 4. Telescope system (optical tube assembly and mount) and clamshell type dome of the OWL-Net installed at Wise observatory in Israel

#### 4. OWL-Net Operation

The entire OWL-Net is connected through the internet and controlled as one system. The operating software was designed to maximize efficiency and productivity of each site. The allocation of observation time for each site is a key element of the mission planning and the main role of the Network Scheduling System (NSS). The NSS determines the priorities of observations based on past observation records, future observability, and user requirements. As a result, an Observation Command File (OCF) is created and transmitted to each site every day. Usually, weekly plans are created in advance for a review, but they are updated every day.

The OCF is an ASCII format file that contains all the information required for observations. Every line in the file is an order for actions, for example, movement to a specific position, filter selection, chopper speed, and exposure time. Lines in the files are activated sequentially. Fig. 5 shows example lines in the OCF. The observed data directly goes to the dedicated storage, and then the data reduction process is performed independent of the observation process. The final results, time and coordinates are recorded in the ASCII format and sent to the HQ.

```

Obs. Action := A20170831-R051
(
  OCF ID           := OCF-20170831-IL1-20170831-R
  Action Start Time := 2017-09-01 01:10:37.454
  Action Duration  := 006.000
  Target ID       := A001F00001
  Target Name     := CRVSAT_2
  Observation Mode := LE0 Orbit Observation(1)
  Requester      := KASI(KRO)
  Request ID     :=
  Data Reduct S/W := LE0/LE0.csh, 1.0
  Request Type   := Regularity(0)
  Pointing Type  := RA Dec(1)
  Tracking Type  := Sliders(1)
  Focus Mode     := Auto(0)
  Focus Value    := 0
  Shot Informations
  {
    1, 1, 1, 1, 2017-09-01 01:11:02.454, 20.640801, 15.202783, 140.413049, 59.726731, 4.845, R(3), 4, 77
    2, 2, 1, 1, 2017-09-01 01:11:28.299, 31.947383, 18.816444, 138.777859, 58.537844, 4.468, R(3), 4, 71
    3, 3, 1, 1, 2017-09-01 01:11:53.767, 35.798818, 20.948834, 138.924787, 56.576799, 4.115, R(3), 4, 65
    4, 4, 1, 1, 2017-09-01 01:12:18.862, 40.409109, 24.080160, 123.136922, 53.698891, 3.798, R(3), 4, 60
    5, 5, 1, 1, 2017-09-01 01:12:43.672, 46.232749, 27.353605, 115.483338, 49.738783, 3.409, R(3), 4, 55
    6, 6, 1, 1, 2017-09-01 01:13:08.171, 53.176375, 30.664525, 108.764224, 44.735135, 3.248, R(3), 4, 51
    7, 7, 1, 1, 2017-09-01 01:13:32.419, 61.630472, 33.768695, 102.409152, 38.554400, 3.084, R(3), 4, 48
    8, 8, 1, 1, 2017-09-01 01:13:56.463, 71.678192, 36.325591, 96.082111, 31.328198, 2.896, R(3), 4, 46
    9, 9, 1, 1, 2017-09-01 01:14:20.359, 83.045707, 37.921266, 91.945954, 23.282999, 2.809, R(3), 4, 44
    10, 10, 1, 1, 2017-09-01 01:14:44.168, 95.806996, 38.225387, 87.626994, 14.773871, 2.798, R(3), 4, 44
    11, 11, 1, 1, 2017-09-01 01:15:07.958, 106.875510, 37.167240, 83.815525, 6.223605, 2.838, R(3), 4, 45
    12, 12, 1, 1, 2017-09-01 01:15:31.796, 117.558829, 34.988833, 80.461189, -1.976883, 2.958, R(3), 4, 47
    13, 13, 1, 1, 2017-09-01 01:15:55.746, 126.740475, 32.864493, 77.409461, -9.551815, 3.121, R(3), 4, 49
    14, 14, 1, 1, 2017-09-01 01:16:19.867, 134.294159, 28.809231, 74.873495, -16.365584, 3.362, R(3), 4, 53
    15, 15, 1, 1, 2017-09-01 01:16:44.249, 140.518961, 25.495168, 72.535934, -22.398765, 3.686, R(3), 4, 57
    16, 16, 1, 1, 2017-09-01 01:17:08.815, 145.615640, 22.286383, 70.445528, -27.688138, 3.946, R(3), 4, 62
    17, 17, 1, 1, 2017-09-01 01:17:33.721, 149.816141, 19.244976, 68.568789, -32.339828, 4.234, R(3), 4, 67
    18, 18, 1, 1, 2017-09-01 01:17:58.957, 153.311228, 16.444131, 66.877595, -36.439263, 4.591, R(3), 4, 73
  }
)

```

Figure 5. An example of an OCF (Observation Command File) which contains all the information needed for the observation

The observation process of the OWL-Net consists of three stages (Fig. 6). The first stage is scheduling. The Network Scheduling System computes the sunset/sunrise time and ephemeris for the targets and then creates an OCF based on the priorities and possibilities of observation.

The second stage involves real actions for observation, which is divided into three sub-stages: preparation, observation, and completion. The preparation step performs the maintenance check and the site warming-up. At the end of this process, the TCS performs the actual observations and saves the results. After the observation process is completed, the maintenance check, the log update process, and the DB update process are followed. At this time, a set of processed data is transmitted to the HQ. The environmental monitoring information for the maintenance check is also transmitted to the HQ and displayed on the monitor in quasi real time. All these tasks are performed completely automatically, without human intervention.

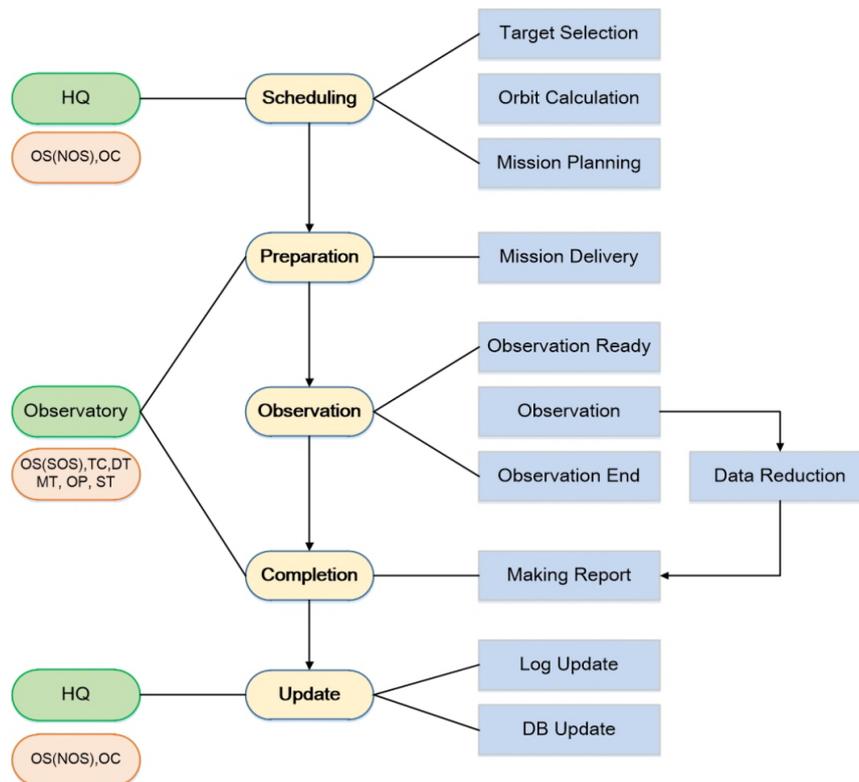


Figure 6. Observation process of the OWL-Net

## 5. Observation Modes

The OWL-Net system has seven observation modes, which are roughly divided into three categories: LEO satellites, MEO/GEO satellites, and astronomical observations. Observation mode 1 is for LEO. To obtain multiple points during one exposure, chopper operation is applied, and each point is time-tagged. A sample image from mode 1 are shown in Fig. 7 (a). Mode 2 involves regional surveys of GEO satellites around a specific position in the GEO belt. A sample image from a regional survey is shown in Fig. 7 (b). Mode 3 is for MEO and GEO satellites. Because their movement speed is much slower than LEO satellites, we adjust the exposure time and chopper manually. A sample image from mode 3 is shown in Fig. 7 (c). Mode 4 involves observation of rather faint GEO satellites and acquisition of their photometric information. In this mode, we deliberately stop the sidereal motion of the telescope mount. The GEO satellites have point-like images in contrast to stars which have flowing images. The amount of light integrated in the point-like images increases in proportion to the exposure time. A sample image from mode 4 is shown in Fig. 7 (d).

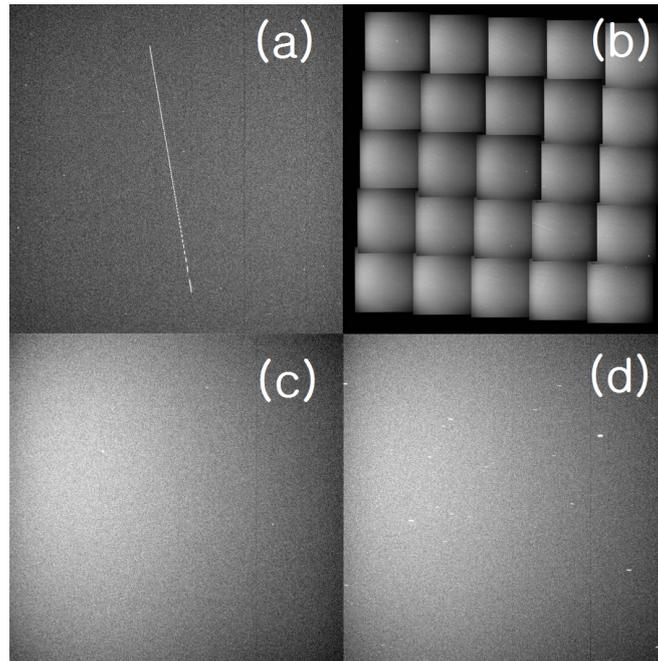


Figure 7. Example images of observation modes for satellites. (a) mode 1: LEO satellites, (b) mode 2: GEO regional survey, (c) mode 3: MEO/GEO satellites, (d) mode 4: fixed GEO observation

Mode 5 is for photometric calibration, not shown here. Mode 5 is basically the same as mode 6. Mode 6 is for astronomical observation of celestial objects. Fig. 8 (a) is a sample image centered at the Draco constellation. Mode 7 is for observation of asteroids that approach close to the Earth. Mode 7 is nearly the same as mode 1 for LEO observation except for the use of filters. Using this observation mode, it is possible to acquire both astrometric and photometric information. Fig. 8 (b) shows an image of 2014 JO25, an asteroid passing near the Earth last year.

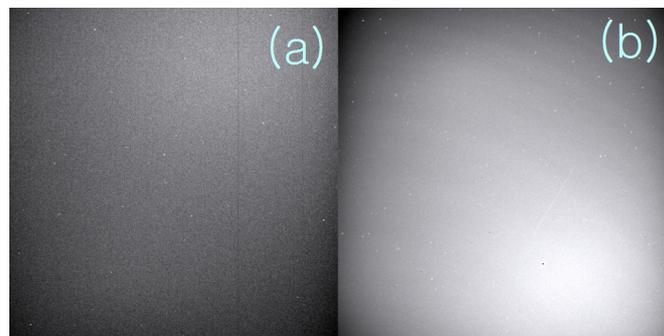


Figure 8. Example images of observation modes for astronomical objects. (a) mode 6: astronomical observation, (b) mode 7: minor planets

## 6. Early Observation Results

Here are examples to show orbit determination capability of the OWL-Net. CRYOSAT-2 is a European satellite for environmental research. Its positional information is well-known with high accuracy. We obtained approximately 1,900 data points at the Israel site during 5 nights in June 2016.

Fig. 9 shows the position difference of the orbital solutions between the observed data and the original TLE data of CRYOSAT-2. The difference in the cross-track and radial direction is less than 500 m. The difference in the in-track direction is larger compared to both directions, but it is still in the range of 1.5 km. Fig. 10 shows the residuals

between the observed points and calculated ones from the orbital solution. Most of them are in the range of 5 arcs, which is the nominal observational error of the OWL-Net system. Fig. 11 shows the positional uncertainty variation of the solution according to the time. The orbit propagation results with the first data diverged, but we can see they converged after adding the second data.

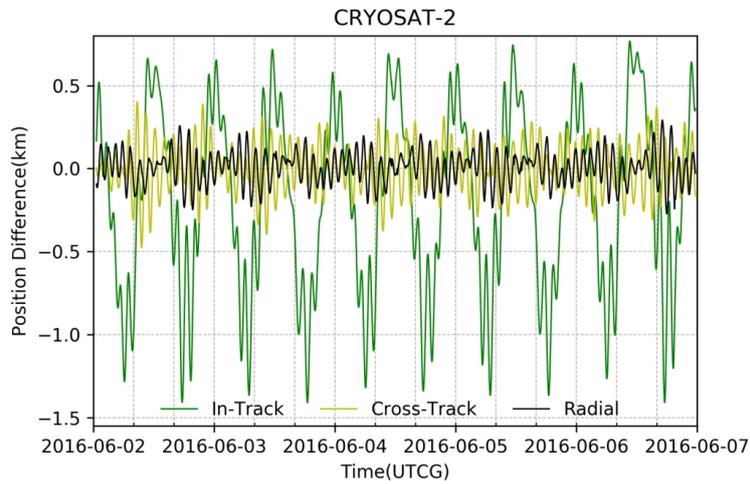


Figure 9. Position difference between orbital solutions from TLEs of CRYOSAT-2 and the optical data observed at the OWL-Net Israel site

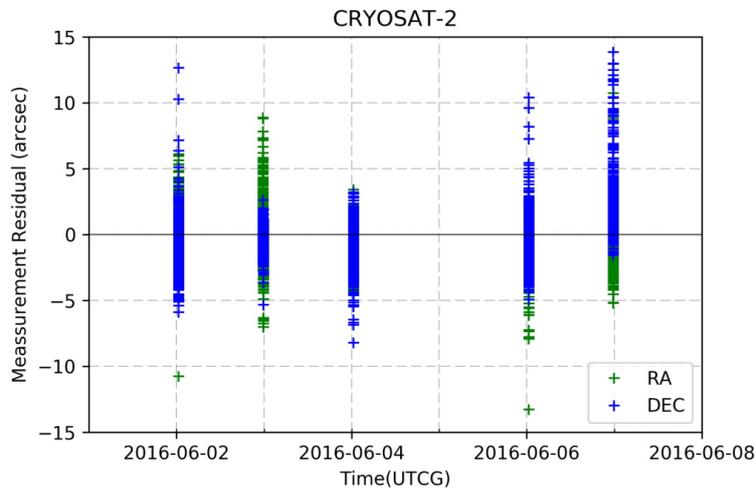


Figure 10. Measurement residuals between the points observed at the OWL-Net Israel site and calculated points from the orbital solution of CRYOSAT-2

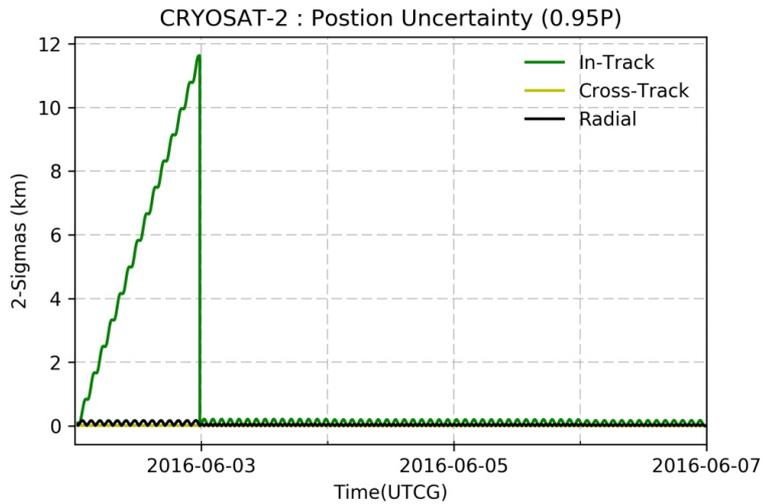


Figure 11. Position uncertainty of the orbital solution of CRYOSAT-2 at 2 sigma level based on the optical data observed at the OWL-Net Israel site

There are same figures are for KOMPSAT-3 (Fig. 12, Fig. 13, Fig. 14). KOMPSAT-3 is one of the Korean earth observation satellites orbiting sun-synchronous LEO. We obtained about 2,800 data points at the Mongolian and Korean sites during 4 nights in May 2017. These figures shared the same pattern with the CRYOSAT-2 case. The position difference in the in-track direction has a slightly higher value than the CRYOSAT-2 case. Although the OWL-Net is still in a test-phase, our conclusion is that the OWL-Net is doing well its job as designed.

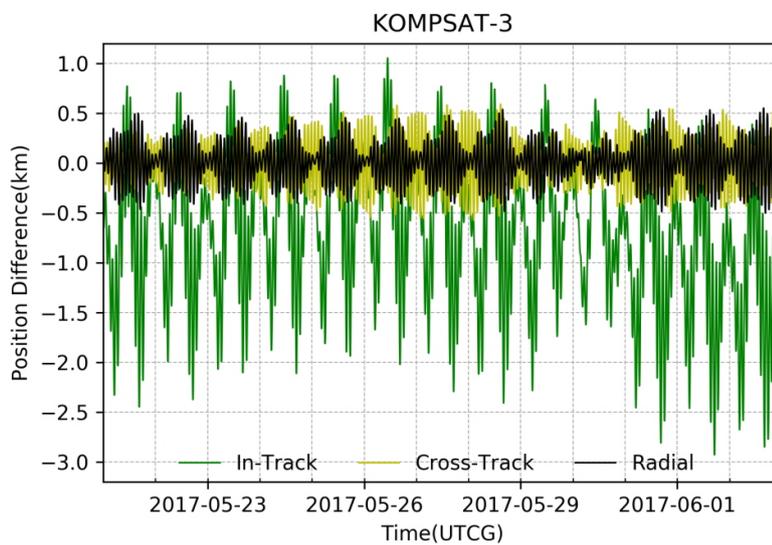


Figure 12. Position difference between orbital solutions from TLEs of KOMPSAT-3 and the optical data observed at the OWL-Net Mongolia and Korea site

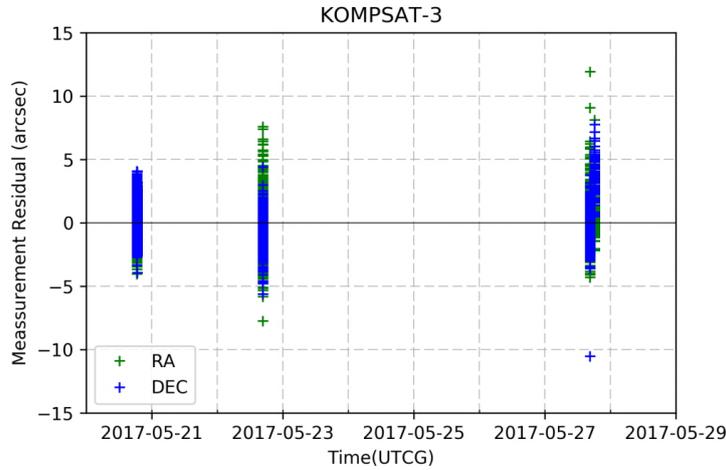


Figure 13. Measurement residuals between the points observed at the OWL-Net Mongolia and Korea site and calculated points from the orbital solution of KOMPSAT-3

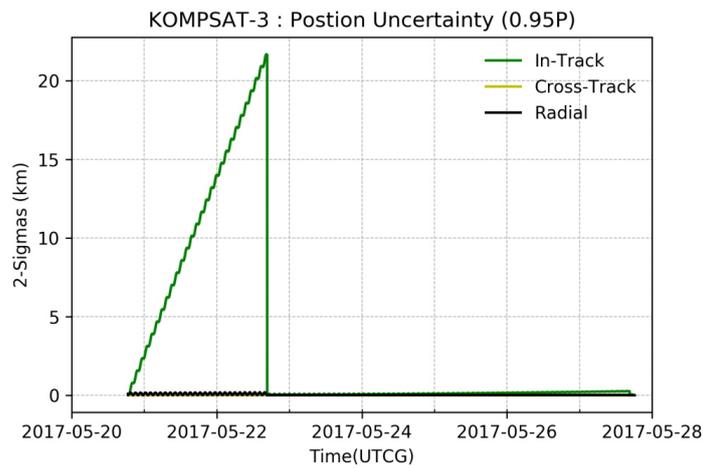


Figure 14. Position uncertainty of the orbital solution of KOMPSAT-3 at 2 sigma level based on the optical data observed at the OWL-Net Mongolia and Korea site

## 7. Discussion

The OWL-Net was designed as a multipurpose system capable of observing GEO satellites as well as LEO satellites and performing astronomical observations. It has seven observation modes for satellites and astronomical objects and it is currently operating in five countries around the world, including Korea. We confirmed the capability of the OWL-Net to track satellites and obtain their orbital information using purely optical means [3]. If we have optical data with the system observation error  $\sim 5$  arcsec, then we could obtain the orbital solution with the positional error within 3 km in the in-track direction. This performance is adequate to secure streaks of a satellite during the next visit and makes it possible to maintain the ephemeris of the satellite. The result shows that an optical system such as the OWL-Net can be a cost-effective alternative for satellite tracking.

The OWL-Net has five stations over the world. These stations are located in the northern hemisphere and are distributed along the longitude to cover most geostationary belt on the sky (Fig. 2). All the five stations share the same configuration and instruments, i.e., they can produce homogeneous data sets. We could expect to produce unprecedented homogeneous data of the geostationary belt.

Our algorithm for image processing to obtain coordinates of satellite streaks is based on astronomical tools such as SExtractor and WCSTools. These tools are old ones, but are fully verified through their long-term use. In fact, we have not encountered problems obtaining coordinates from our images yet. If we consider the efficiency and accuracy of image processing, other alternatives can be used. We are now planning to test other algorithms available now [4] or under development [5].

The observation mode for minor planets has mixed characteristics of modes for satellites and astronomical objects. This technology opens new possibilities for minor planet research. Recently observed minor planets, 2014 JO25 and 1123 Florence, can serve as unique examples for a new method for minor planet observation.

The installation of the OWL-Net system at the five sites over the world was completed at the end of 2016. The test-phase operation of the whole system started in early 2017, although test runs for individual sites started from 2014 [6]. We are now concentrating on the calibration and validation of the system and expecting full-scale operation next year. According to our early results, an optical system based on robotic operation can be a versatile tool for the study of both satellites and celestial objects.

## 8. References

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