Simultaneous Optical and Laser Space Objects Tracking

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The goal of the presented experiments is the development of new optical tracking techniques of space objects, namely the space debris, based on simultaneous Optical detection (CCD tracking) and laser measurements:

1) the CCD tracking of laser illuminated object
2) the simultaneous CCD tracking and object laser ranging
3) the nanosecond laser time-tagging of the CCD tracking

The first two techniques can be performed on co-operative retroreflector equipped objects (high power lasers could be further used even for non co-operative [1]).

While the third one is applicable to any space object, the space debris in particular.

Add new applications for Satellite Laser Ranging stations

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Applications (1/2)
First insight

**Classic optical detection**

- Technique for determination the orbit of object, based on object’s angular positions measurements
- Object illuminated only by Sun
- Telescope synchronized to catalogued stars + object in FOV during exposure -> angular coordinates -> pixels
- 2 Time-tags in the CCD image (Exposure start time and Exposure length) -> times -> pixels
- Problems of the accurate time-tags assigning to subpixels positions in the image (edges detections from signal curve with low SNR)

**Laser usage in Optical detection:**

- Additional object illumination
  - cooperative objects - Low power laser (usually stronger back reflections (retroreflectors nature) than by Sun only illumination)
  - noncooperative objects - High power laser (object shape reflectivity)
- Additional Time-tags in the CCD images – Low or High power laser
  Time-tags with *nanosecond time precision and subpixel positions* by laser photons backscattered by atmosphere

Object illuminated by Sun only

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Applications (2/2)
Details

High Precision 3D solution
Object laser ranging + Optical detection with laser time-tagging

- **cooperative objects**
  - Calibration of Optical detection systems

- **noncooperative objects**
  - High power laser strong to get enough returns -> Ranging results
    -> Orbit estimation
  - Low power laser (only few returns) -> combination of ranging data +
    high precision angular data (laser time-tagging) -> Orbit estimation

2D solution

Optical detection with laser time-tagging

- **cooperative** or **noncooperative objects**
  - several times more of high precision angular data (laser time-tagging)
    -> Orbit estimation

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High Precision 3D solution

Optical detection with laser time-tagging

Observatory - Satellite laser ranging station in Graz, Austria

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**Laser Time-Tags without returns**

**Classic optical detection**
- Object illuminated by Sun only
- Only 2 Time-tags (Exposure start time and Exposure length)
- Times for Time-tags – milisecond up to microsecond scale (GPS)
- Problems of the accurate time-tags assigning to subpixels positions in the image (edges detections from signal curve with low SNR)
- Accuracy - up to 1 arcsecond
- Nr. of angular measurements during 1 path: usually ~ 10 values/path,
\[
\text{max} \sim \frac{\text{telescope positioning} + \text{exposure} + \text{image readout times}}{\text{path time}}
\]

**Optical detection with Laser Time-Tagging**
- Object illuminated by Sun and partially by Low-power laser (or by High-power laser only)
- Basic 2 Time-tags (Exposure start time and Exposure length)
- Higher precision of the Times for Time-tags – nanosecond scale
- Higher accuracy of time-tags assigning to subpixels positions in the image – All image area of Atmospherically back-scattered photons could be used - not only edges detections from signal curve
- Accuracy – better than 1 arcsecond (first results ~0.2 arcsec/s)
- Nr. of angular measurements during 1 path: higher productivity
\[
\text{Nr. of optical measurements} \times \text{Nr. of laser time-tags in image}
\]

Object illuminated by Sun only

Object illuminated by Sun and partially by Low-power laser

Laser beam reflected from satellite

Lageos1

Cirrus clouds

1-5: Laser gaps = 10 Time-tags by laser beam photons backscattered from atmosphere
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Satellite Laser Ranging System (SLR) station in Graz

The SLR station has been modified to provide laser power output modulation (selection of output pulses – gating of Pockel’s cells) to serve as a time tagger for the laser illuminated exposures.

The laser is "switched off" for the preset time interval (e.g. 50, 100 or 500 milliseconds, etc.) each one second. The precision of the time-tags is on the nanosecond scale. The time scale accuracy connected to GPS is better than 100 ns.

**Laser transmitter:** HighQLaser, Diode pumped Nd:Van, $\lambda=532$ nm, repetition rate 2 kHz, Pulse length 8 psec, 400 $\mu$J/pulse, Average power up to 1W

**Beam divergence** $\theta \sim 100$ $\mu$rad

**Detector:** C-SPAD; Range up to 30 000 km

**Ranging accuracy** ~few mm for Retroreflector equipped satellites in distances of 400-30’000 km

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Experiment Setup (2/3)
Telescope and CCD cameras for Optical detection

**CCD Telescope:**
Meade LX200 16”, f/10
Tracking precision 5 arcmin (worse now)

**Focal reducers:** f/6.3 or f/3.3

**Field of View:**
CCD1: ~ 23x15 arcmin, 1.8x1.8 arcsec/pixel (bin 3x3)
CCD2: ~ 16.6x12.5 arcmin, 1.2x1.2 arcsec/pixel (bin 2x2)
EMCCD: ~ 9.3x7.0 arcmin, 0.85x0.85 arcsec/pixel

(EMCCD = CCD with internal Electron multiplying register)

**CCD cameras:**
1: SBIG ST-10ME
   - Pixel Array: 2184x1472
   - Pixel Size: 6.8x6.8 μm
   - CCD Size: 14.9x10 mm
   - Filter: 488-574 nm, green pass

2: SBIG ST-2000XM
   - Pixel Array: 1600x1200
   - Pixel Size: 7.4x7.4 μm
   - CCD Size: 11.8x8.9 mm
   - Filter: no filter

**EMCCD camera:**
Andor LucaEM
   - Pixel Array: 658x496
   - Pixel Size: 10x10 μm
   - CCD Size: 6.58x4.96 mm
   - Filter: no filter

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1. Object path prediction

2. SLR Station:
   - Telescope - able smooth real-time object tracking (~ 1 arcsecond)
     - diameter depending on object shape and reflectivity
   - Laser – pulse (min. repetition rate > 1 Hz (higher is better)
     - depending on Optical detection system FOV, object speed and nr. of laser time-tags)
   - Pulses gating system + events timing system with high accuracy + photon detector*
   - Sensitive camera – CCD, EMCCD, ISIT, etc. (optical feedback)

3. Optical detection system:
   - Telescope
     - object tracking precision (~ 5 arcminutes or better, depending on Optical det. system FOV)
     - diameter depending on object shape and reflectivity
   - Sensitive Low-Noise Camera – CCD, EMCCD
     - Pixel size, Quantum efficiency depending on object speed, shape and reflectivity
       (+ telescope properties)

* photon detector is not necessary

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Experiment results 1

Topex Satellite (range ~ 1340 km)

- Predicted satellite range: 2511.3 km
- Laser measured satellite range: 2387.137284 km
- => measured orbit height: 1348.1 km
- Orbit height computed from tracking data range: 1353.7 km

CCD: SBIG ST-10 ME

Exposure:
- Start: 2005-03-17 UTC 02:54:43.712
- Length: 5s

Object illumination: Laser illumination only

Time stamps - laser off 100 ms each 1 sec

Blue: Tracked object optical trace densitogram with time stamps
Red: Moving AVG (Average) Window graph of optical trace densitogram
(Window: width 5 pixels, height 5 pixels)

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Experiment results 2

Ajisai (EGP) Satellite (range ~ 1500 km)

- Predicted satellite range: 2232.8 km
- Laser measured satellite range: 2233.109195 km ➞ measured orbit height: 1493.3 km
- Orbit height computed from tracking data range: 1472.1 km

CCD: SBIG ST-2000 XM

Exposure:
- Start: 2005-07-04 UTC 01:47:19.433
- Length: 2s

Object illumination: Sun and Laser illumination
Time stamps - laser off 100 ms each 1 sec

AJISAI (EGP) is spinning satellite covered with mirrors and retroreflectors.
Adding Time-stamps in atmosphere could increase precision of its spin speed and spin axes orientation measurements

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Lageos1 Satellite (range ~ 5860 km)

- Predicted satellite range: 7089.7 km
- Laser measured satellite range: 7089.368978 km
- Measured orbit height: 5846.4 km
- Orbit height computed from tracking data range: 5862.1 km

**CCD:** SBIG ST-10 ME

**Exposure:**
- Start: 2005-03-17 UTC 01:22:46.018
- Length: 10s

**Object illumination:** Sun and Laser illumination

Time stamps - laser off 100 ms each 1 sec

Moving AVG Window graphs of densitograms with time stamps
(Window: width 5 pixels, height 5 pixels)

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Glonass 87 Satellite (range ~ 19 100 km)
- Predicted satellite range: 20 551.7 km
- Laser measured satellite range: 20 551.623858 km
- Measured orbit height: 19 196.6 km
- Orbit height computed from tracking data range: 19 181.3 km

CCD: Andor Luca EMCCD

Exposure:
- Start: 2006-09-10 UTC 01:24:09
- Length: 3s

Object illumination: Sun and Laser illumination
Time stamps - laser off 500 ms each 1 sec

Blue: Optical trace densitogram with time stamps
Red: Moving AVG (Average) Window graph of optical trace densitogram
(Window: width 2 pixels, height 5 pixels)

Higher SNR

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Problems

Atmosphere density – low density => less back-scattered photons

Object tracking Accuracy and Smoothness of the tracking laser movement

Distance between Laser and CCD telescopes
  - too far => low back scattered photons
  - too close => low tags resolution - merging

Position of Object, SLR station and CCD telescopes – “Blind Angles”

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Conclusion

Results

The high accuracy and density of laser ranging data and/or additional precise laser Time-tags in the CCD image, the atmospherically back scattered photons, can contribute to the high solution stability of computed orbits from data based on a single tracking location within a single pass.

These facts can result in increase the observation productivity and orbit computation stability in comparison to the techniques used recently.

Cooperative targets tracking has been tested by our group in a series of experiments involving combined optical and laser tracking of space cooperative objects at the Observatory of Graz, Austria, March 15-17, 2005 and in September 2006. The laser time-tagging method was also tested on following satellites with retroreflectors: **Champ** (~ 400 km), **ERS2** (~ 800km), **GPS-35** (~ 20000 km).

Non-cooperative target tracking has been tested by B. Greene [1].


Future

• Improvement of precision of the image processing methods (now under development)

• Method testing on non-cooperative objects

• Other image time-tagging methods development

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Thank you for your attention.

I’ll be glad if you will contact me with any comments or interest to try these techniques 😊

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