UN-COOPERATIVE TARGETS SESSION SUMMARY

Chair: Craig Smith

This short session received fascinating papers from laser ranging groups attempting the most difficult of SLR activities - that is ranging to un-cooperative targets.

From Shanghai Observatory we heard about the numerous upgrades to the system there towards the development of precision tracking for un-cooperative targets (ie targets that do not carry retro-reflectors). We wish Shanghai Observatory well in this endeavor.

From Czechoslovakia and the Graz SLR station in Austria a new technique for provide simultaneous optical and laser tracking of targets was described.

The Experimental Laser Ranging System for Space Debris at Shanghai

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Abstract

The paper introduces the performance of the experimental laser ranging system for space debris at the Shanghai Observatory. The output of laser is 2J in 532nm, 10ns, 20Hz, 40W. A new transmitting telescope with the aperture of 210mm is used, and the other parts of the ranging system are the same with the routine SLR system in Shanghai. The ranging system is under testing now.

Introduction

China has launched many spacecrafts into space and had produced many space debris during 30 years. China is one of the members of IADC (Inter-Agency Space Debris Coordination Committee). It is necessary for China to pay great attention to reduce damages from space debris in cooperation with international community. The project of laser ranging to space debris at Shanghai Astronomical Observatory is supported by the Chinese Space Agency. An experimental laser ranging system for space debris at Shanghai is set up in 2006. The goals of the project are as follows: 1) Development of the technology for space debris laser tracking. 2) Experimental observations and orbit determinations for space debris, not routine observations.

2. Performance of the system

The major parts of the space debris ranging system are the same with the SLR system at Shanghai. A China-made 40W Q-switched Nd:YAG laser has been installed and is located at the neighbor room to the mode-locked laser for SLR. There are ten Nd:YAG rods in the laser with the output of 2J in 532nm, 10ns width, 20Hz repetition, 0.6mrad divergence. A new transmitting telescope with 210 mm aperture was installed and replaced the old one with 150mm aperture for better collimating beam. The testing of laser ranging to the satellites with retro-reflectors has been done. The next step will try to ranging to uncooperative space targets soon.

Some photos for the system are shown as follows.

Fig.1. *The Optical Observation Site at Shanghai Observatory, CHINA*

Fig.2. *SLR House in Shanghai*

Fig.3. *SLR Telescope(Aperture 600mm)*

Fig.4. *Electronics Room*

Fig.5. *High Power Laser & Power Supply, Chiller*

Fig.6. *Output of High Power Laser*

Fig.7. *Inside of the 40W Pulsed Nd:YAG Laser*

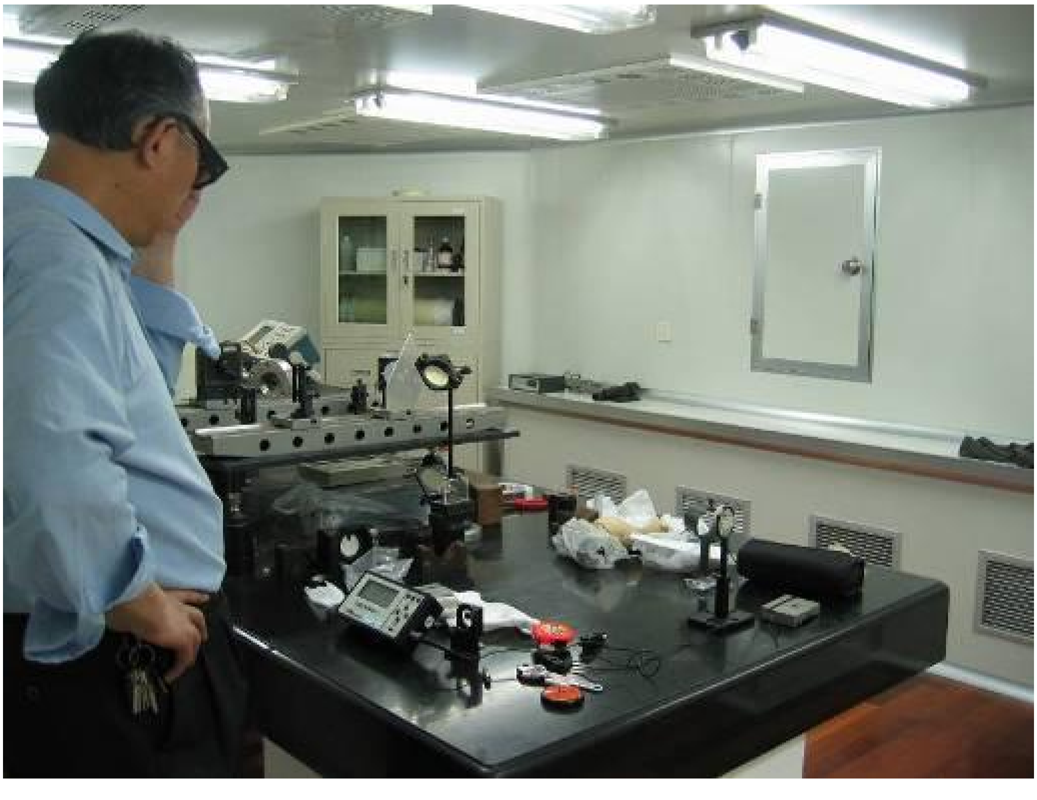

Fig.8. *Coupling Optics*

Fig.9. *Laser Firing (2J, 20Hz, 40W in 532nm)*

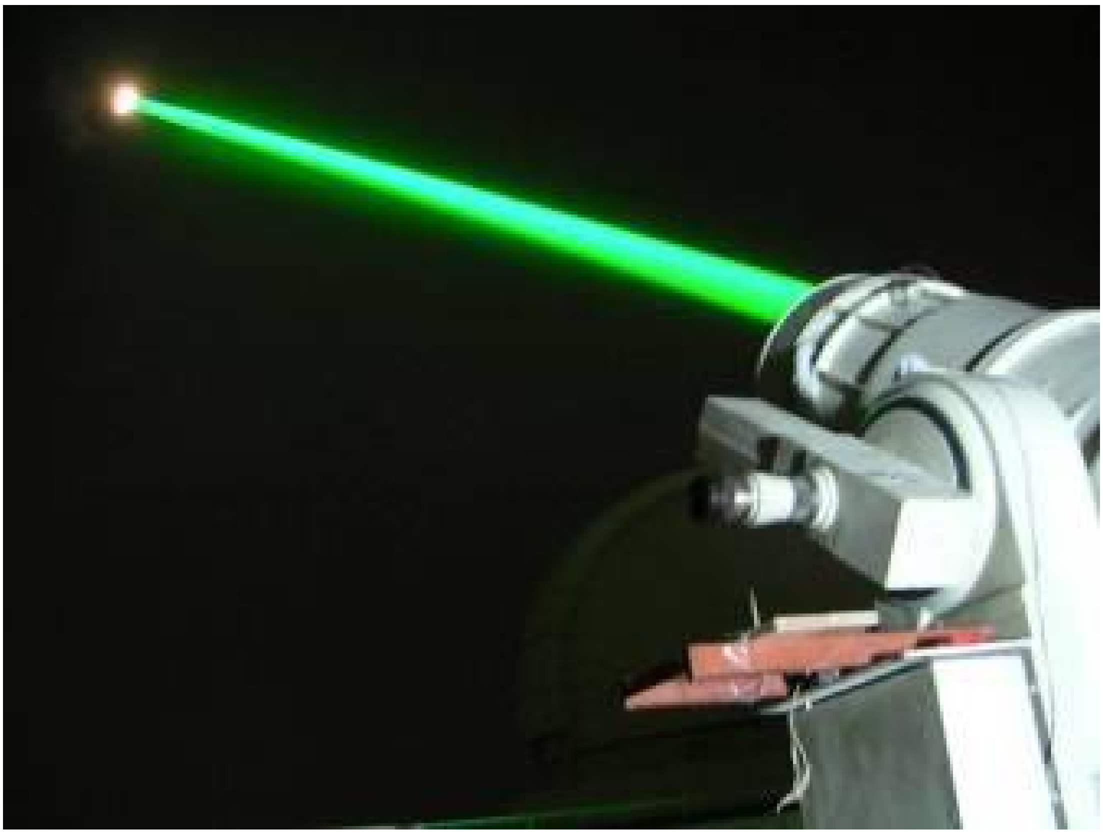

Fig.10. *Laser Firing*

Simultaneous Optical and Laser Space Objects Tracking

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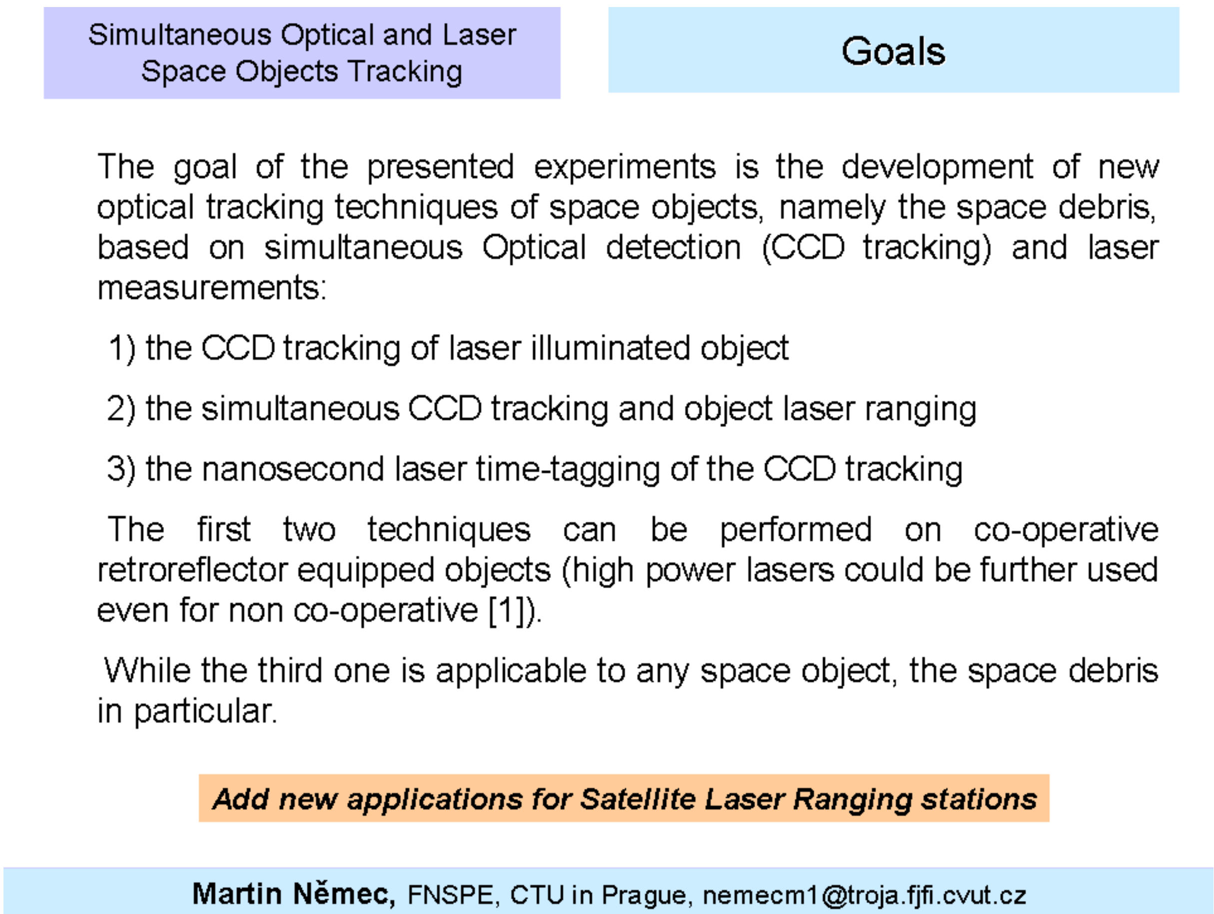
Abstract

The goal of the presented experiments is the development of new optical tracking techniques for space objects, namely space debris, based on simultaneous CCD and laser measurements: the CCD tracking of a laser illuminated object, the simultaneous CCD tracking and laser ranging and the laser time-tagging of the CCD tracking. The first two experiments can be performed on cooperative - corner retro-reflectors equipped satellites while the third one is applicable to any space object and to space debris in particular. The high accuracy and density of laser ranging data and additional Time-tags in the CCD image, atmospherically back scattered photons, can contribute to the solution stability of computed orbits from data based even on a single tracking location within a single pass.



Simultaneous Optical and Laser Space Objects Tracking

Applications (1/2)
First insight

Classic optical detection

• Technique for determination the orbit of object, based on object's angular positions measurements

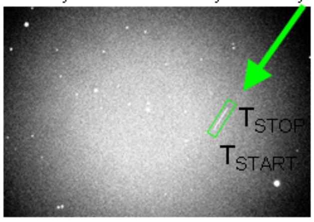
• Object illuminated only by Sun

• 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)

Object illuminated by Sun only



Laser usage in Optical detection:

- Additional object illumination
  - cooperative objects - Low power laser (usually stronger back reflections (retroreflectros 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

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Simultaneous Optical and Laser Space Objects Tracking

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

High Precision 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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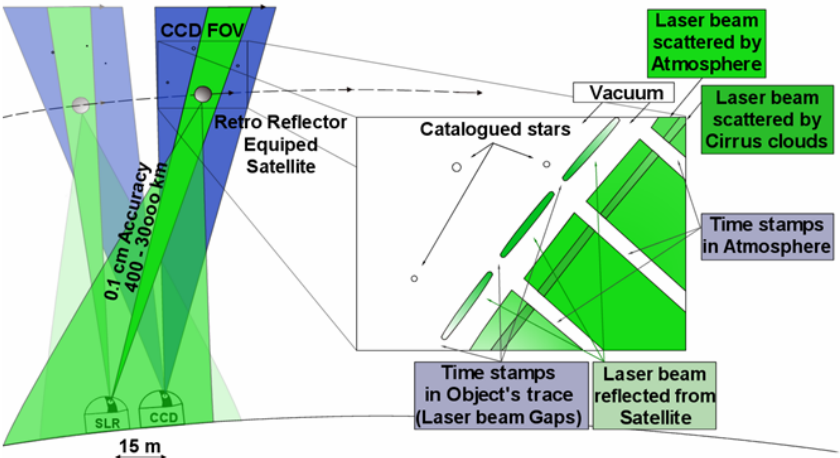
Simultaneous Optical and Laser Space Objects Tracking

Project scheme

High Precision 3D solution

Optical detection with laser time-tagging



Observatory - Satellite laser ranging station in Graz, Austria

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Simultaneous Optical and Laser Space Objects Tracking

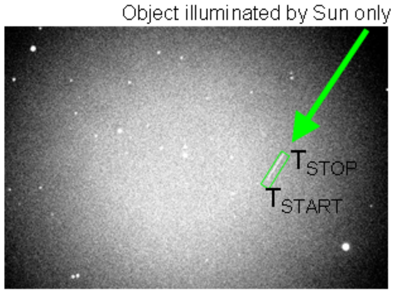
Laser Time-Tags without returns

Classic optical detection

- Object illuminated by Sun only
- Only 2 Time-tags (Exposure start time and Exposure length) (more Time-tags using Advanced methods with e.g. rotating shutter)
- 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,

$$\max \sim \frac{\text{path time}}{\text{telescope positioning +exposure +image readout times}}$$

Object illuminated by Sun only

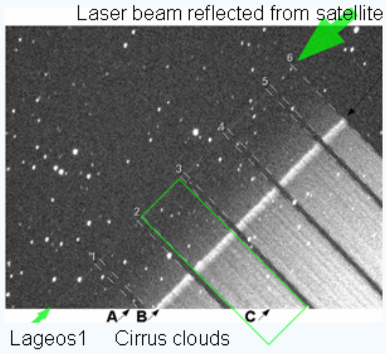


Optical detection with Laser Time-Tagging

- 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) + **more additional Time-tags** by laser beam modulation or by selection of pulses to be send to the object
- **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**
  Nr. of optical measurements x Nr. of laser time-tags in image

High Precision 2D solution

Laser beam reflected from satellite

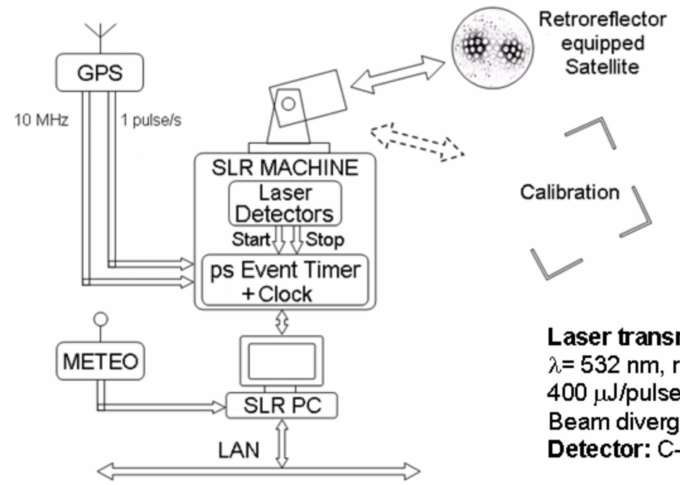


1-5: Laser gaps = 10 Time-tags by laser beam photons backscattered from atmosphere

Simultaneous Optical and Laser Space Objects Tracking

Experiment Setup (1/3)
SLR system

Satellite Laser Ranging System (SLR) station in Graz



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

Laser transmitter: HighQLaser, Diode pumped Nd:Van, λ= 532 nm, repetition rate 2 kHz, Pulse length 8 psec, 400 μJ/pulse, Average power up to 1W
Beam divergence θ ~100 μrad
Detector: C-SPAD; Range up to 30 000 km

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.

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Simultaneous Optical and Laser Space Objects Tracking

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

CCD Telescope:
Meade LX200 16", f/10
Tracking precission 5 arcmin (worse now)

Focal reducers: f/6.3 or f/3.3

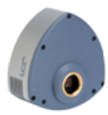
Field of View:
CCD1: ~ 23x15 arcmin, 1.8x1.8 arcsec/pixel (bin 3x3)
CCD2: ~ 16.6x12.5 arcmin, 1.2x1.2 arcsec/pixel (bin 2x2)
EMCCD: ~ 9.3x7.0 arcmin, 0.85x0.85 arcsec/pixel

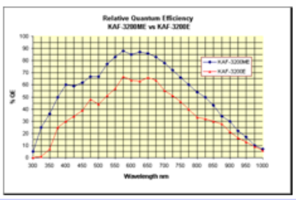
(EMCCD = CCD with internal Electron multiplying register)

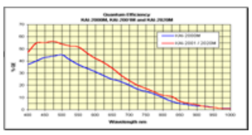
CCD cameras:
1: SBIG ST-10ME
Pixel Array: 2184x1472
Pixel Size: 6.8x6.8 μmxμm
CCD Size: 14.9x10 mmxmm
Filter:
488-574 nm, green pass

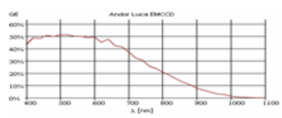
2: SBIG ST-2000XM
Pixel Array: 1600x1200
Pixel Size: 7.4x7.4 μmxμm
CCD Size: 11.8x8.9 mmxmm
Filter:
no filter

EMCCD camera:
Andor Luca EM
Pixel Array: 658x496
Pixel Size: 10x10 μmxμm
CCD Size: 6.58x4.96 mmxmm
Filter:
no filter









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Simultaneous Optical and Laser Space Objects Tracking

Experiment Setup (3/3)

Minimal system configurations

High Precision 3D solution

High Precision 2D solution

* photon detector is not necessary

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)

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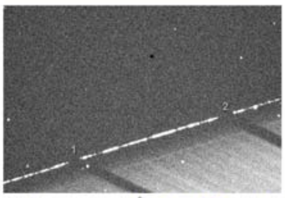
Simultaneous Optical and Laser Space Objects Tracking

Experiment results 1



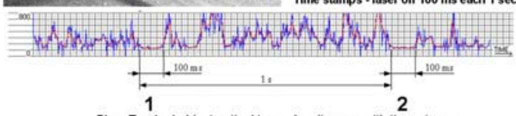
Topex Satellite (range ~ 1340 km)

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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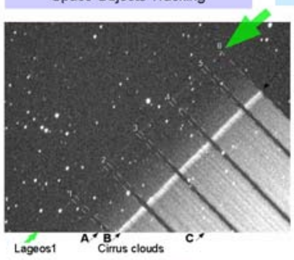
Simultaneous Optical and Laser Space Objects Tracking

Experiment results 3



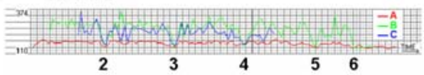
Lageos1 Satellite (range ~ 5860 km)

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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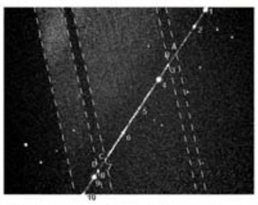
Simultaneous Optical and Laser Space Objects Tracking

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

Point	Time [s]	Position [x,y]
A	21.00000002	[550.37 , 145.97]
B	21.10000005	[527.67 , 180.28]
C	22.00000003	[323.42 , 489.05]
D	22.10000001	[300.73 , 523.36]

Base Time: 2005-07-04 UTC 01:47:19.433

Point	Time [s]	Position [x,y]
1	20.5983	[641.71 , 7.89]
2	20.7552	[606.01 , 61.85]
3	21.1217	[522.88 , 187.52]
4	21.2545	[492.82 , 232.96]
5	21.5231	[431.77 , 325.26]

Point	Time [s]	Position [x,y]
6	21.7560	[378.69 , 405.49]
7	22.0012	[323.27 , 489.28]
8	22.1024	[300.26 , 524.07]
9	22.1623	[286.64 , 544.66]
10	22.3192	[250.94 , 598.62]

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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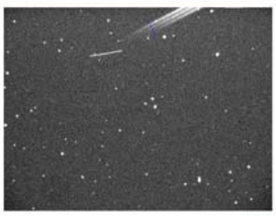
Simultaneous Optical and Laser Space Objects Tracking

Experiment results 4



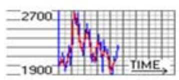
Glonass 87 Satellite (range ~ 19 100 km)

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



Higher SNR

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

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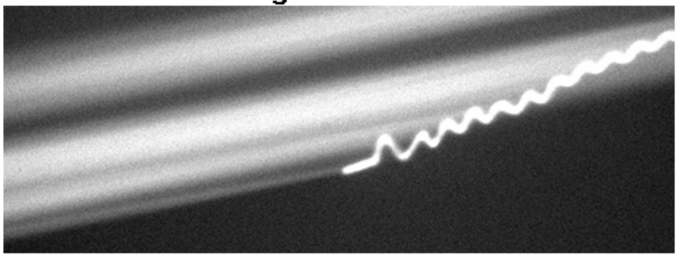
Simultaneous Optical and Laser Space Objects Tracking

Problems

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

Object tracking Accuracy and Smoothness of the tracking laser movement

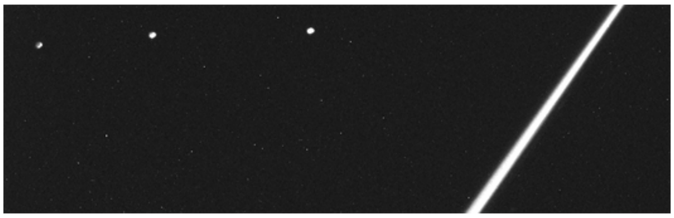


Distance between Laser and CCD telescopes

– 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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Simultaneous Optical and Laser Space Objects Tracking

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** (~ 20ooo km).

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

[1] B. Greene et. al., *Advanced Techniques at the EOS Space Research Centre*, 14th International Laser Ranging Workshop, San Fernando, Spain, June 7-11, 2004, published in Boletin ROA No. 4/2004, Real Instituto Observatorion de la Armada, en San Fernando, ISSN 1131-5040, 2004

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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