Outline

- Recent trends
  - Ground Sampling Distance (GSD)
  - Data rate requirement
- Past space laser communication projects
  - ETS-VI/LCE project
  - OICETS/LUCE project
  - NeFOC project (airborne mission)
- Future laser communication projects
  - SOCRATES/SOTA project
  - VSOTA project
  - Shindai-sat project
  - JAXA’s pre-project
- Activities on Free-space QKD in NICT
- Concluding remarks
GSD trends for Earth observation satellites

Data rate requirement after 2020

- Data rate >~20 Gbps
- Sensor resolution <GSD 10 cm
- Memory size >~1 Tbytes
- Digitized bits >~14 bits

Gbps-class laser communication is inevitable for data download from observation satellites.
Trends of data rate for space laser comm.

Trends of optical receiver sensitivity
# Space-based laser communication programs

<table>
<thead>
<tr>
<th>Past</th>
<th>NASA/US</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994: <strong>ETS-VI</strong> (GEO-GND) 0.8μm/0.5μm, IMDD, 1Mbps</td>
<td>2000: <strong>STRV-2</strong> (LEO-GND, Failure) 0.8μm, IMDD, 1.2Gbps</td>
<td>2001: <strong>SILEX</strong> (GEO-LEO, GEO-GND, GEO-Air) 0.8μm, IMDD, 50Mbps</td>
</tr>
<tr>
<td>2006: <strong>OICETS</strong> (LEO-GEO, LEO-GND) 0.8μm, IMDD, 50Mbps</td>
<td>2001: <strong>GeoLiTE</strong> (GEO-GND)</td>
<td>- 2008: <strong>TerraSAR-X</strong> (LEO-LEO, LEO-GND) 1.06μm, homodyne BPSK, 5.6Gbps</td>
</tr>
<tr>
<td>2011: <strong>NeFOC</strong> (Air-GND) 1.5μm, QPSK, 40Gbps</td>
<td>2008: <strong>NFIRE</strong> (LEO-LEO) 1.06μm, homodyne BPSK, 5.6Gbps</td>
<td>- 2009: DARPA <strong>ORCA</strong> (Air-Air-GND) TRL6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Future plan</th>
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<tbody>
<tr>
<td>2013: <strong>RISESAT/VSOTA</strong> (LEO-GND) 0.98/1.5μm, IMDD, ~1kbps</td>
<td>2013: <strong>LLCD/LADEE</strong> (Lunar-GND) 1.5μm, PPM, 622Mbps</td>
<td>- 2012: <strong>OSIRIS</strong> 1.5μm, IMDD, 20Mbps</td>
</tr>
<tr>
<td>- 2013: <strong>SOCRATES/SOTA</strong> (LEO-GND) 0.98/1.5μm, IMDD, 10Mbps</td>
<td>2016: <strong>LCRD</strong> (Laser Communications Relay Demonstration) 1.5μm, DPSK/PPM, 2.8G/622Mbps</td>
<td>- 2013: <strong>Alphasat/EDRS</strong> (European Data Relay System) 1.06μm, homodyne BPSK, ~1.8Gbps</td>
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</tbody>
</table>

## Space laser communications in NICT

- GMS-2
- GMS-3
- GMS-4
- GMS-5
- **ETS-VI**
- **LCE**
- **ARTEMIS OPALE** (ESA)
- **GEO-LEO** Two-way LaserCom.
- **OICETS**
- **LUCE** (JAXA)
- **TerraSAR-X**
- **LCTSX** (DLR)
- **NICT OGS** (1.5m telescope System)

NICT optical ground station

ETS-VI (GEO)

Laser Communication Equipment (LCE)

- 1 Mbps bi-directional optical link experiment
- 22 kg, 60 W onboard equipment verification

Experimental configuration with JPL

ETS-VI

After 15 Hours Cruising

ETS-VI

Optical Link

Telemetry/Command

NASDA TKSC

NASA Goldstone Station

JPL Optical Ground Station

Data Transmission and Communication Using International ISDN Link

NICT/CRL Optical Ground Station
Decoded telemetry data via optical communication link with 1 Mbps

Measured 1995/12/8

Sampling freq. 500Hz


Satellite size 0.78x1.1x1.5 m
Mass 570 kg
Mission life 1 year
Altitude 610 km (circular)
Inclination 98 deg.

Courtesy of JAXA
International laser communications experiment

ESA/ARTEMIS       OICETS/Kirari satellite

Data acquisition of laser beam propagation and link establishment at different sites

Modeling the atmospheric propagation channels and learning site diversity effect

Examining optimum error correcting codes and the best combination of OGSs

Contribution to the standardization in ITU-R and CCSDS*.

International cooperation between 4 OGSs

Statistics of link establishment

- Probability of success during all the experiments
  - NICT: 49.1 %
  - NASA JPL: 57.1 %
  - DLR: 60.0 %
  - ESA: 88.9 %
- Total probability of success between Earth and space:
  - \(1 - \[(1-0.491) \times (1-0.571) \times (1-0.60) \times (1-0.889)\] = 0.9903
- Four OSGs combination will help to download massive data from space with the probability of 99%.

Statistics of link establishment at NICT
Acquisition and tracking

<table>
<thead>
<tr>
<th>Wide FOV CCD</th>
<th>CCD at Tx bench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guide Telescope</td>
<td>CCD at Rx bench</td>
</tr>
</tbody>
</table>

BER performances

Uplink BER characteristics

Downlink BER characteristics
Polarization characteristics through space-to-ground atmospheric paths

Polarization rms error: 1.6° (2.8%)
DOP: 99.4 ± 4.4%

Toyoshima, et. al., Optics Express, 17(25), (2009)

Laser communication infrastructure for micro-satellites

Short term space verification of component level technologies by micro-satellites

High-end communications by mid/small satellites (5~ years)

Quasi realtime data transmission via site diversity

Offline transmission only

Short term space verification by micro satellites (2~3 years)
Small Optical TrAnsponder (SOTA) mission

Main objectives:
- In-orbit verification of acquisition, tracking and pointing performances
- Data acquisition of laser beam propagation at various wavelengths
- Laser communication experiments with coding
- Basic experiments for satellite QKD
- Experiments with international Optical Ground Stations (OGSs)

<table>
<thead>
<tr>
<th>Basic experimental items for satellite QKD</th>
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<tbody>
<tr>
<td>Protocol</td>
</tr>
<tr>
<td>Clock rate</td>
</tr>
<tr>
<td>Mean photon number</td>
</tr>
<tr>
<td>Measurement</td>
</tr>
<tr>
<td>QBER</td>
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<tr>
<td>Dark count rate</td>
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</table>
RISESAT Project Background

Hodoyoshi Program (Professor Nakasuka, The University of Tokyo)
- Development of five 50kg class micro-satellites
- Launch is planned in the Japanese fiscal year of 2013
- One of the satellites is an international scientific micro-satellite (RISESAT) (Tohoku University is responsible for the project management)

RISESAT: Rapid International Scientific Experiment Satellite
Mission Objectives
- Demonstrate international scientific missions by inviting instruments from abroad
- Investigation on advanced bus system technologies for future scientific micro-satellites
- Development of a reliable, robust and cost effective micro-satellite bus system

Expected effects
- Realization of mechanism of rapid demonstration of scientific missions in the future
- Improvement of microsatellite technologies which enables future challenging scientific missions
- Commercial spin-off of providing cost-effective microsatellite bus systems

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RISESAT System Specifications

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<thead>
<tr>
<th>Size and weight</th>
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<tbody>
<tr>
<td>size</td>
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<tr>
<td>weight</td>
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<tr>
<th>Orbit</th>
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<tbody>
<tr>
<td>type</td>
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<tr>
<td>local time</td>
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<tr>
<td>altitude</td>
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<tr>
<td>inclination</td>
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<tr>
<th>Attitude determination and control</th>
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<tbody>
<tr>
<td>method</td>
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<tr>
<td>pointing accuracy</td>
</tr>
<tr>
<td>pointing stability sensors</td>
</tr>
<tr>
<td>star sensor (2), FOG (3-axes),</td>
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<tr>
<td>magnetometer (3-axes), GPS receiver (1),</td>
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<tr>
<td>course and accurate sun sensors(4)</td>
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<tr>
<td>actuators</td>
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<tr>
<th>Power supply</th>
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<tbody>
<tr>
<td>solar cells</td>
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<td></td>
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<tr>
<td>battery unit</td>
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<tr>
<td>max. power generation</td>
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<tr>
<td>max. power consumption</td>
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<tr>
<th>Communication</th>
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<tbody>
<tr>
<td>command uplink</td>
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<tr>
<td>HK downlink</td>
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<tr>
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<tr>
<td>Mission Data downlink</td>
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</table>

Launch configuration

After panel deployment
2. Recent R&D

High Speed FSO (NeFOC Project)

High speed free space optical communication network for data transmission from Airplane or LEO satellite

- Large amount of Data transmission in short period of time is required.

Outline of the system

Problems for link connection

1. Abrupt disconnection of link caused by cloud and handover.
2. Degradation of communication efficiency caused by connecting different communication media.
3. Fluctuation of the received signal caused by the attitude variation and the vibration of the vehicle and atmospheric distortion.

Key Technologies

- Efficient link protocol for high speed data transmission (40Gbps) and a quick link recovery technique.
- Digital coherent detection scheme and highly efficient error correction method using LDPC.
- Small and light onboard optical terminal which perform coarse and fine pointing and tracking.
- Adaptive optics which compensate atmospheric turbulence effect based on real-time feedback control.
2. Recent R&D (High Speed FSO)
Developed Optical Terminal

Mobile Terminal

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Size</td>
<td>380×420×531mm</td>
</tr>
<tr>
<td>Optical I/O Diameter (window)</td>
<td>110mm</td>
</tr>
<tr>
<td>Az-axes Angle Range</td>
<td>±280deg.</td>
</tr>
<tr>
<td>El-axes Angle Range</td>
<td>±115deg.</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>1.77×10⁻⁴ kg m² (EL)</td>
</tr>
<tr>
<td></td>
<td>0.87 kg m² (AZ)</td>
</tr>
<tr>
<td>Angle Resolution</td>
<td>0.01 deg.</td>
</tr>
<tr>
<td>Total Weight</td>
<td>39kg</td>
</tr>
</tbody>
</table>

Outdoor communication link test using the mobile terminal

1. Contraption points of this mission

Baseline of quantum cryptography

One-time pad cryptography

Ideal random data (common key)

- 1 bit key is needed for 1 bit send
- Unconditional security

Basic quantum cryptography

- Unconditional security
- Data rate = QKD rate (very slow) (less than 100kbps) (less than 20dB loss)
- All end-users need big facilities (e.g., optical antenna)

Contraption points

Random expansion

- high-speed (possible to actual use)
- Not unconditional security (but, it's not practical issue)

These contrapotions make a difference in practical use

Server-client architecture

- Optical Ground Stations are shared (small load for end users)
- Ground fiber network is used to short range QKD
2. Total System Image (in future actual use phase)

- >10~100km: QKD over satellites
- <10~100km: QKD over ground fiber network

3. Plan for Flight Demonstration

**Objective**
Acquire knowledge and knowhow for actual use.

1. **[Demonstration of QKD]**
   - QKD will be done between satellite and ground station.

2. **[Demonstration of quantum cryptography]**
   - Downlink some data from satellite using quantum cryptography.

3. **[Demonstration of wideband com.]**
   - Wideband communication will be done between ground stations using random expansion.

4. **[Demonstration of actual use]**
   - Open this communication line for common people via internet to get many operation case data.

### Overall Plan

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<tbody>
<tr>
<td>Development and Demonstration Phase</td>
<td>Basic Study</td>
<td>System Study</td>
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<tr>
<td>(Tentative)</td>
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</table>
Live demo: Free-space laser communication and QKD experiments in UQCC conference

Measurement of Cn² between two buildings

Distance: 1.35km, Height of the link: 138m
Conceptual designs for satellite QKD

Terminal model 1: WCP + decoy

- Protocol: WCP+decoy
- Antenna diameter: 125 mm
- Antenna type: Cassegrain type and coude path
- Size: 305 x 300 x 125 mm
- Mass: 46 kg
- Power consumption: 97.4 W (nominal) 138 W (peak)

Terminal model 2: Entanglement (E91)

- Protocol: Entanglement (E91)
- Optical antenna diameter: 100 mm
- Antenna type: Cassegrain and Elbow type
- Size: 400 x 250 x 500 mm
- Mass: 37.5 kg
- Power consumption: 119.7 W

Hybrid entanglement generation and verification experiment

- **Alice**: Polarization analysis
  - Half-waveplate + PBS
  - Si detector

- **Bob**: Time-bin (phase/time) analysis
  - Planer Lightwave circuit (PLC)
  - InGaAs detector (gated mode)
Coincidence results

Measurement results
- Visibility > 85.3% (beyond 70.7% of Bell’s inequality)
  - Polarization and time-bin entanglement
    - Hybrid entanglement
    - Available for QKD

Key generation rate
- Raw key ~1430 bps
- Sift key ~720 bps

Error rate
- 4.8%


High speed laser communication links and global QKD networks

Delivery of quantum keys via aircraft and satellites

SAR-applications
Observation data download from aircraft and satellites
Acquisition/tracking
Polarization QKD
Time-bin QKD
Entanglement conversion
Entanglement source
SSPD
Optical fiber networks
NICT in-house technologies
Concluding remarks

- Recent trends of GSD and data rates for RF and optical links were introduced.
- Past Japanese laser communication missions such as ETS-VI/LCE and OICETS/LUCE projects were introduced.
- As an application to micro-satellites, new NICT’s laser communication missions called SOCRATES/SOTA and RISESAT/VSOTA were introduced, and these micro-satellites are expected to be launched in 2013.
- Airborne 40-Gbps laser communication demonstration between a balloon and a mobile station called NeFOC project was introduced.
- Shindai-sat and JAXA’s pre-project were introduced.
- Activities on Free-space QKD in NICT were shown.