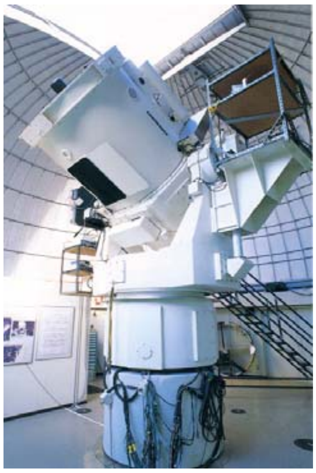
Demonstrations on Space Laser Communications in Japan

Morio Toyoshima and Yoshihisa Takayama

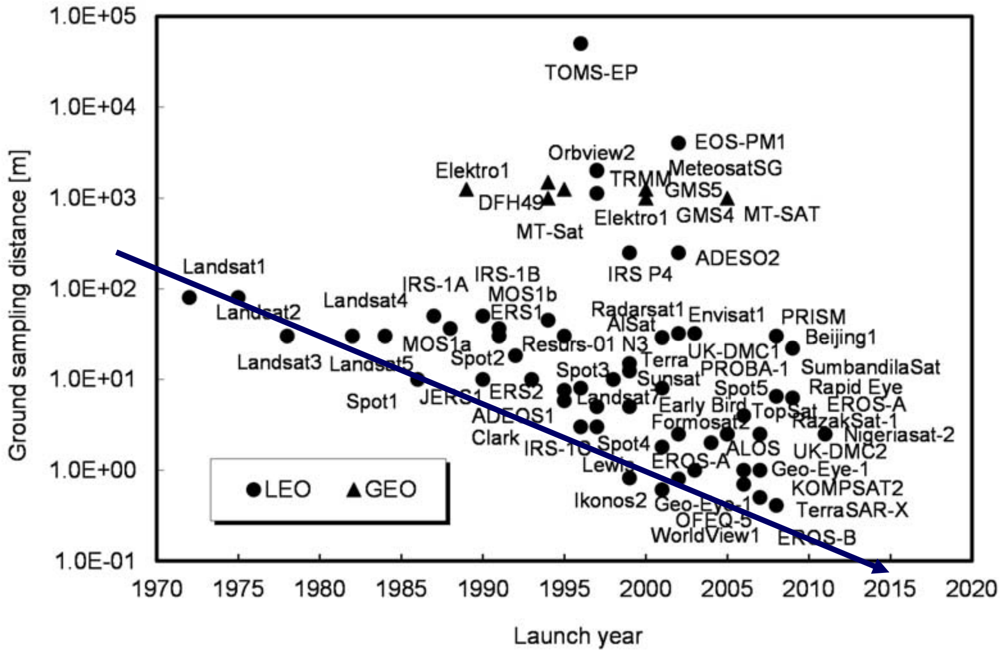
Space Communication Systems Laboratory
Wireless Network Research Institute
National Institute of Information and Communications Technology (NICT)
Mail: morio@nict.go.jp

Outline

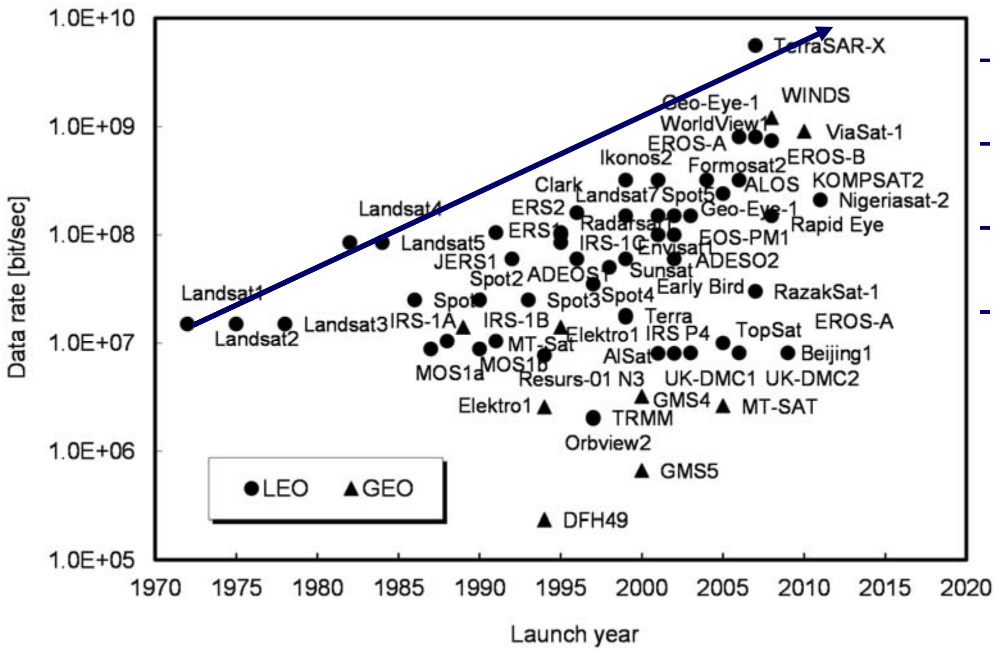
- Recent trends
  - Ground Sampling Distance (GSD)
  - Data rate requirement
- Past space laser communication projects
  - ETS-VI/LCE project
  - OICETS/LUCE project
  - NeFOC project (airborne mission)
- Future laser communication projects
  - SOCRATES/SOTA project
  - VSOTA project
  - Shindai-sat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



GSD trends for Earth observation satellites



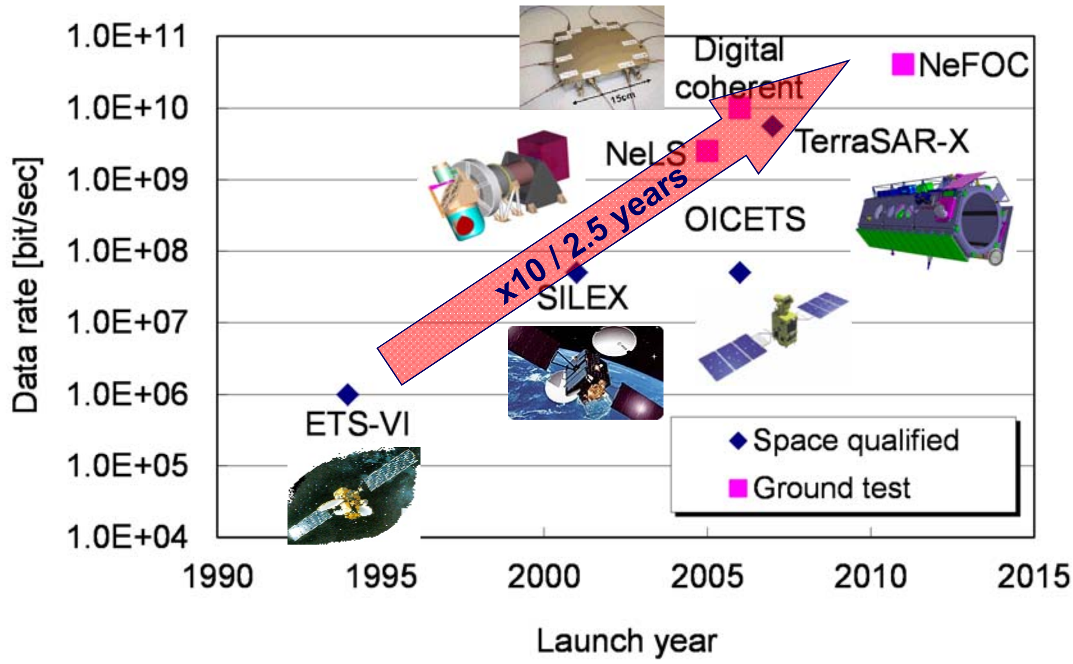
Data rate requirement after 2020



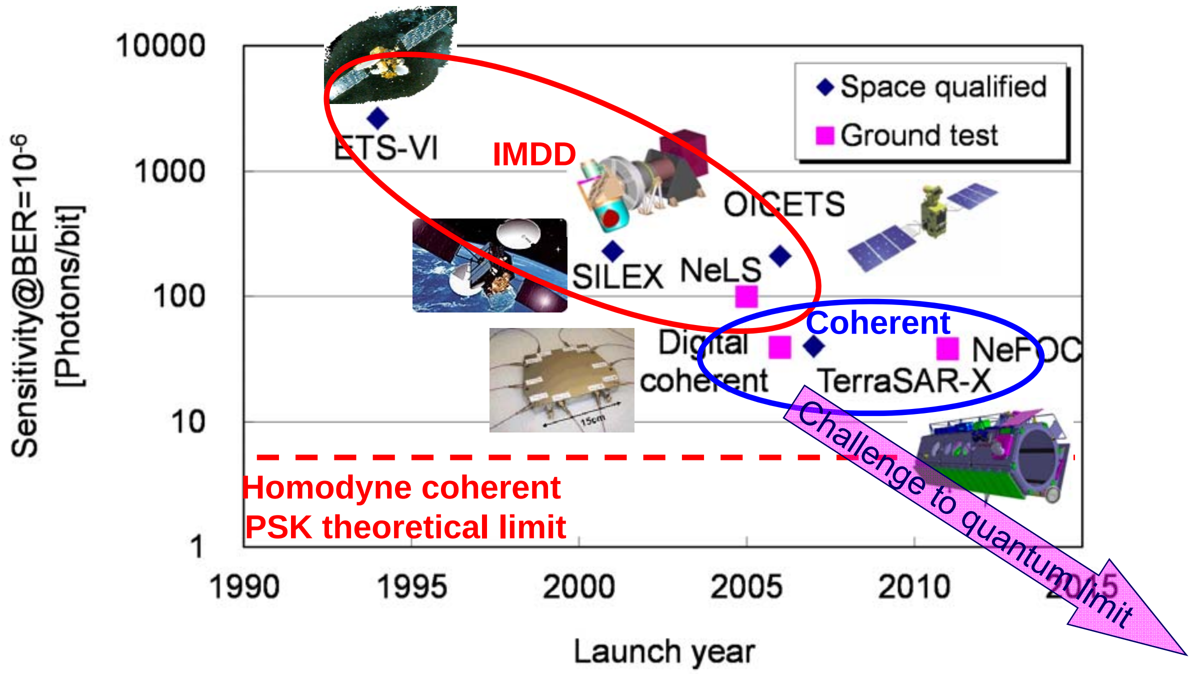
- Data rate
  >~20 Gbps
- Sensor resolution
  <GSD 10 cm
- Memory size
  >~1 Tbytes
- Digitized bits
  >~14 bits

Gbps-class laser communication is inevitable for data download from observation satellites.

Trends of data rate for space laser comm.



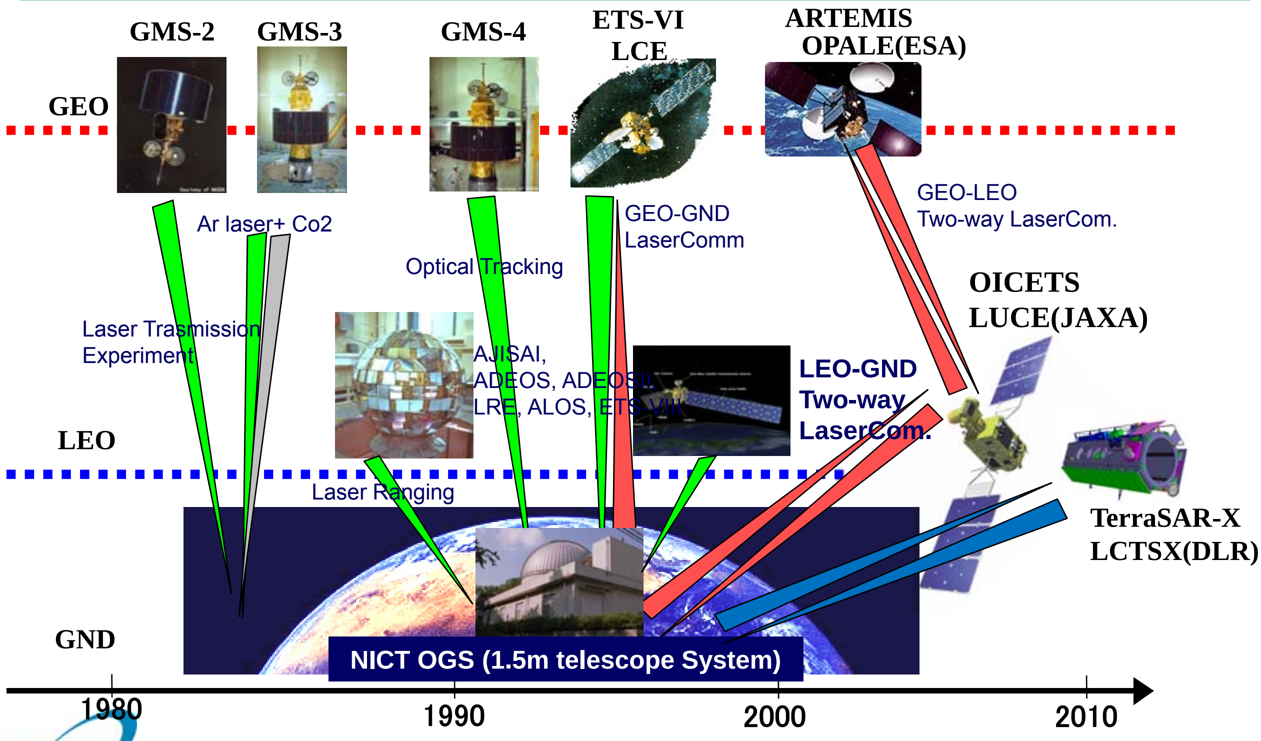
Trends of optical receiver sensitivity



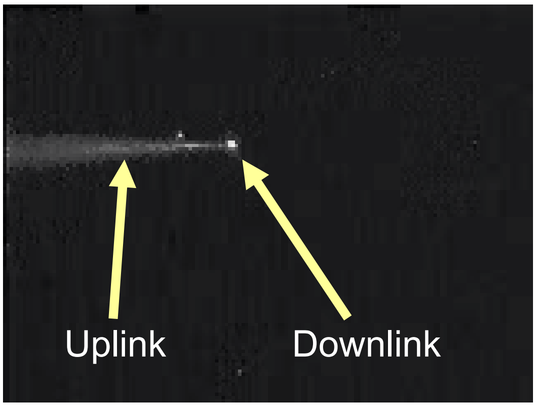
Space-based laser communication programs

	Asia/Japan	NASA/US	Europe
Past	- 1994: **ETS-VI** (GEO-GND) 0.8μm/0.5μm, IMDD, 1Mbps - 2006: **OICETS** (LEO-GEO,LEO-GND) 0.8μm, IMDD, 50Mbps - 2011: **NeFOC** (Air-GND) 1.5μm, QPSK, 40Gbps	- 2000: **STRV-2** (LEO-GND, Failure) 0.8μm, IMDD, 1.2Gbps - 2001: **GeoLITE** (GEO-GND) - 2008: **NFIRE** (LEO-LEO) 1.06μm, homodyne BPSK, 5.6Gbps - 2009: DARPA **ORCA** (Air-Air-GND) TRL6	- 2001: **SILEX** (GEO-LEO, GEO-GND, GEO-Air) 0.8μm, IMDD, 50Mbps - 2008: **TerraSAR-X** (LEO-LEO, LEO-GND) 1.06μm, homodyne BPSK, 5.6Gbps
Future plan	- 2013: **RISESAT/ VSOTA** (LEO-GND) 0.98/1.5μm, IMDD, ~1kbps - 2013: **SOCRATES/ SOTA** (LEO-GND) 0.98/1.5μm, IMDD, 10Mbps	- 2013: **LLCD/LADEE** (Lunar-GND) 1.5μm, PPM, 622Mbps - 2016: **LCRD** (Laser Communications Relay Demonstration) 1.5μm, DPSK/PPM, 2.8G/622Mbps - DARPA **System F6**	- 2012: **OSIRIS** 1.5μm, IMDD, 20Mbps - 2013: **Alphasat/EDRS** (European Data Relay System) 1.06μm, homodyne BPSK, ~1.8Gbps

Space laser communications in NICT

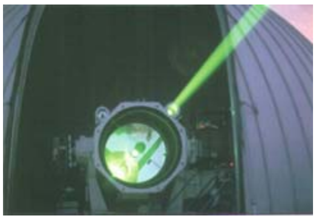


Engineering Test Satellite VI (ETS-VI) Experiments (Dec. 1994 - July 1996)



Laser Communication Equipment (LCE)

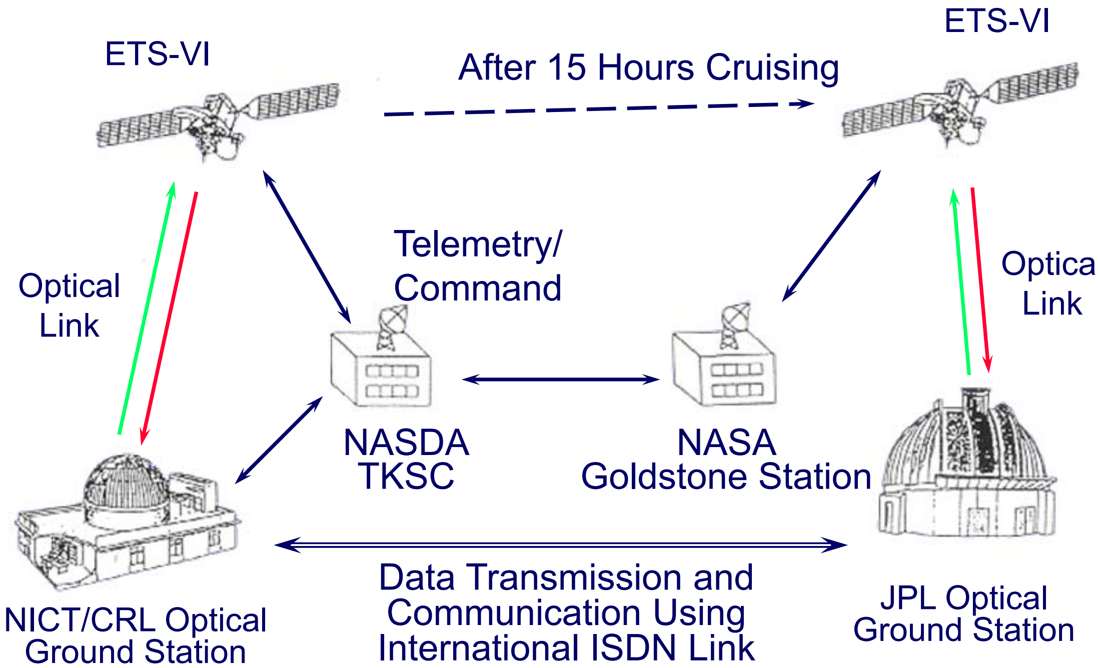
ETS-VI (GEO)



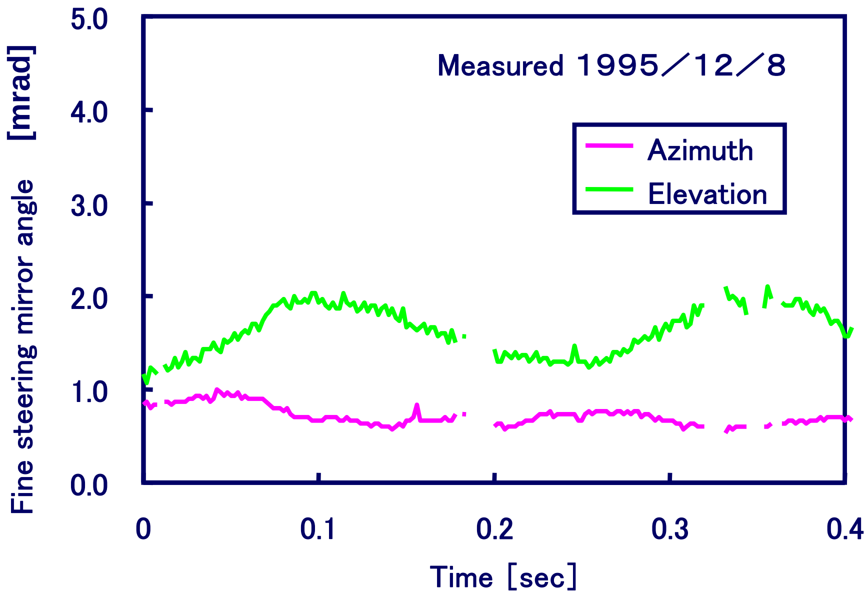
NICT optical ground station

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

Experimental configuration with JPL

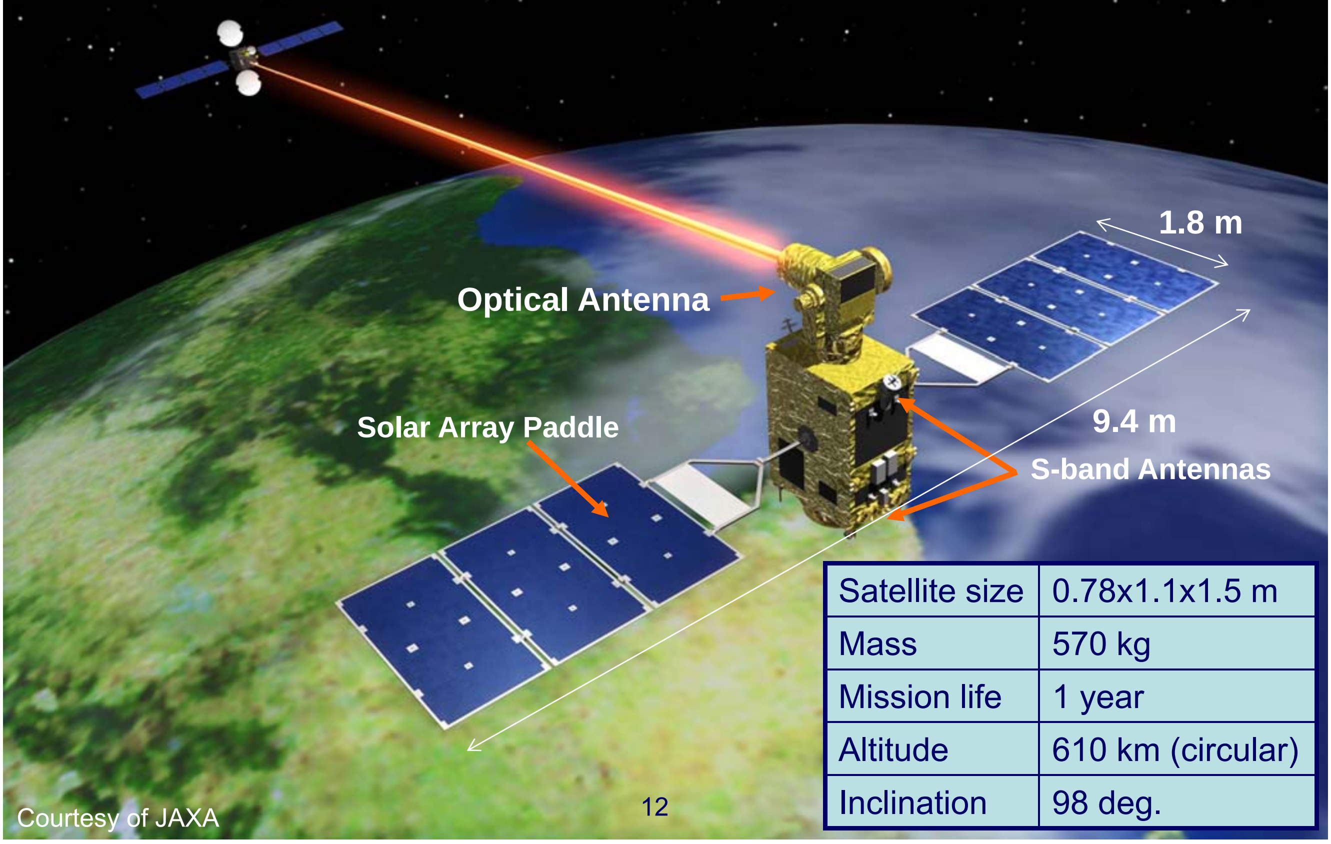


Decoded telemetry data via optical communication link with 1 Mbps



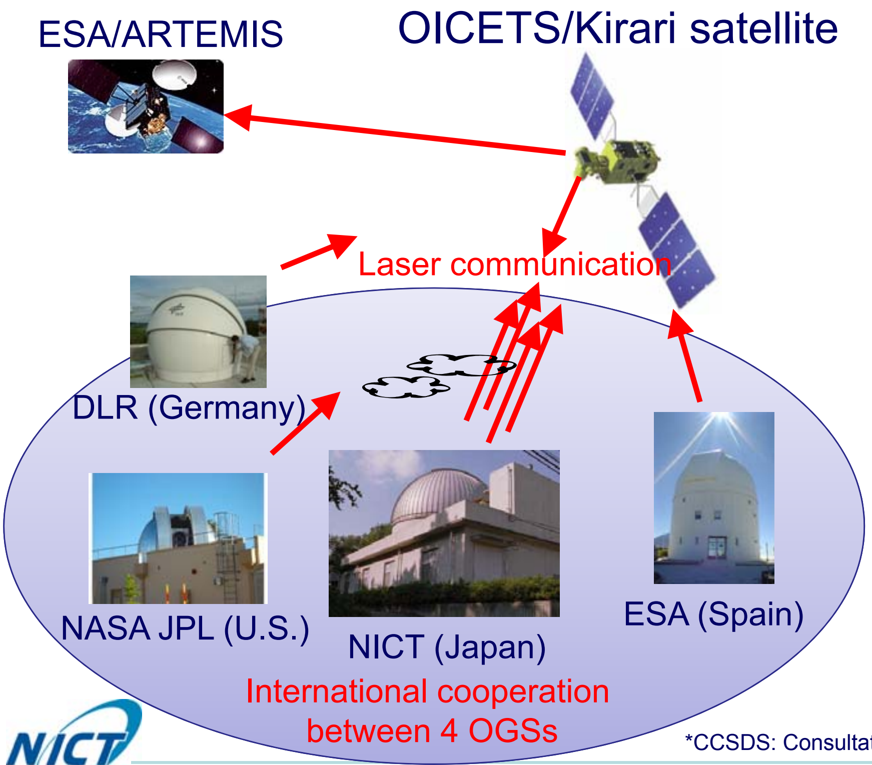
Sampling freq. 500Hz

Optical Inter-orbit Communication Engineering Test Satellite (OICETS) (August 2005 – Sept. 2009)



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

International laser communications experiment



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

Modeling the atmospheric propagation channels and learning site diversity effect

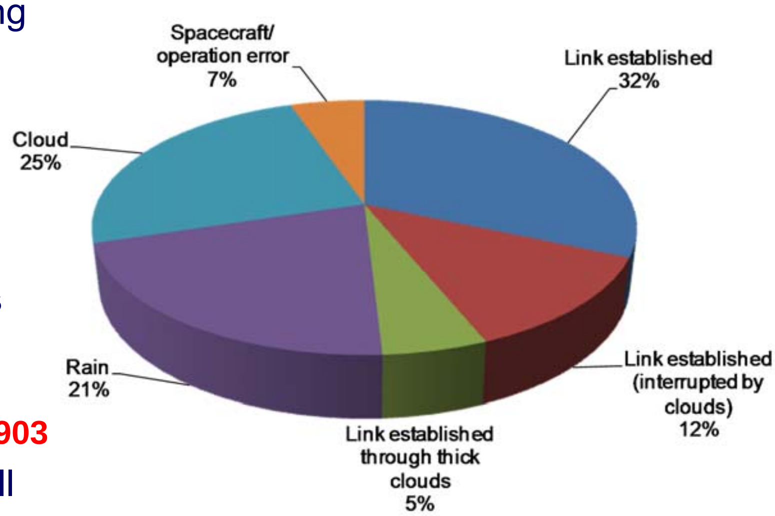
Examining optimum error correcting codes and the best combination of OGSs

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

*CCSDS: Consultative Committee for Space Data Systems

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)x(1-0.571) x(1-0.60)x(1-0.889)] = **0.9903**
- Four OSGs combination will help to download massive data from space with the probability of 99%.

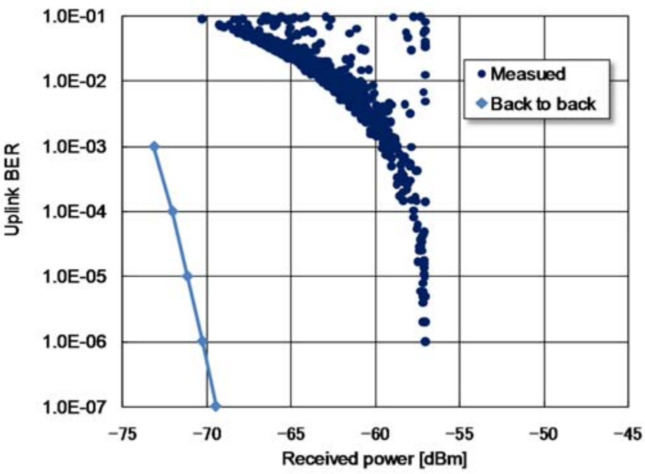


Statistics of link establishment at NICT

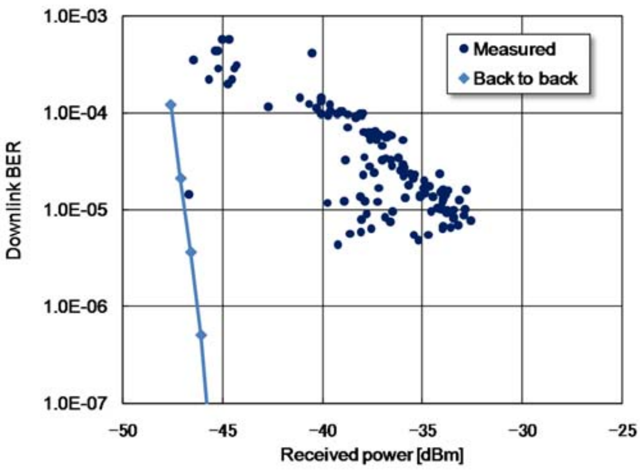
Acquisition and tracking

Wide FOV CCD	CCD at Tx bench
Guide Telescope	CCD at Rx bench

BER performances

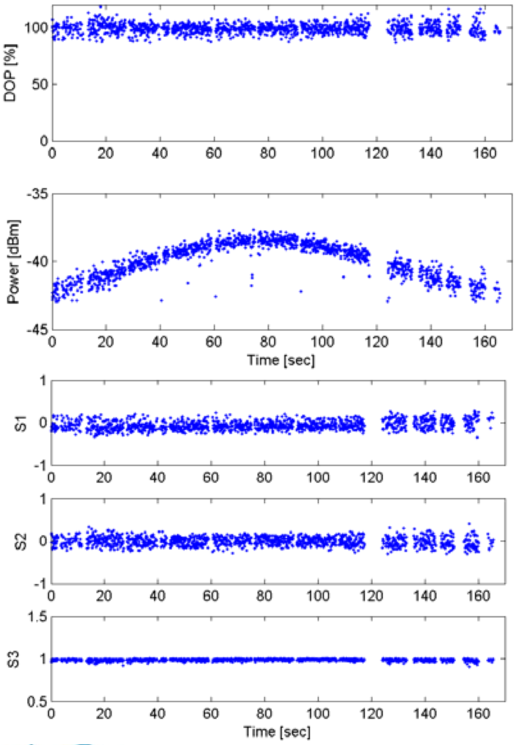


Uplink BER characteristics

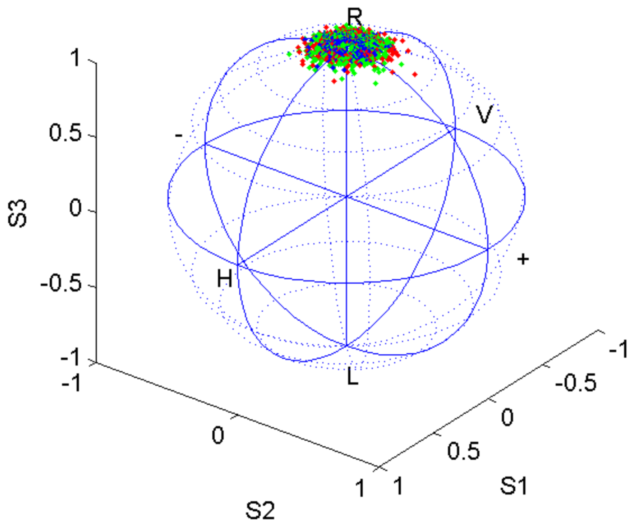


Downlink BER characteristics

Polarization characteristics through space-to-ground atmospheric paths



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

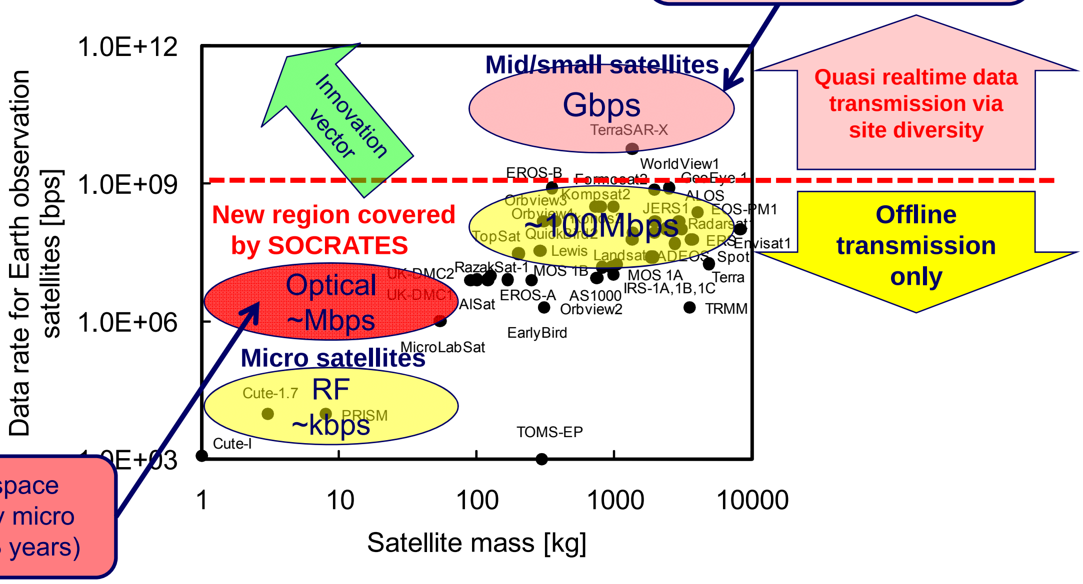


Toyoshima, et. al., Optics Express, 17(25), (2009)

Laser communication infrastructure for micro-satellites

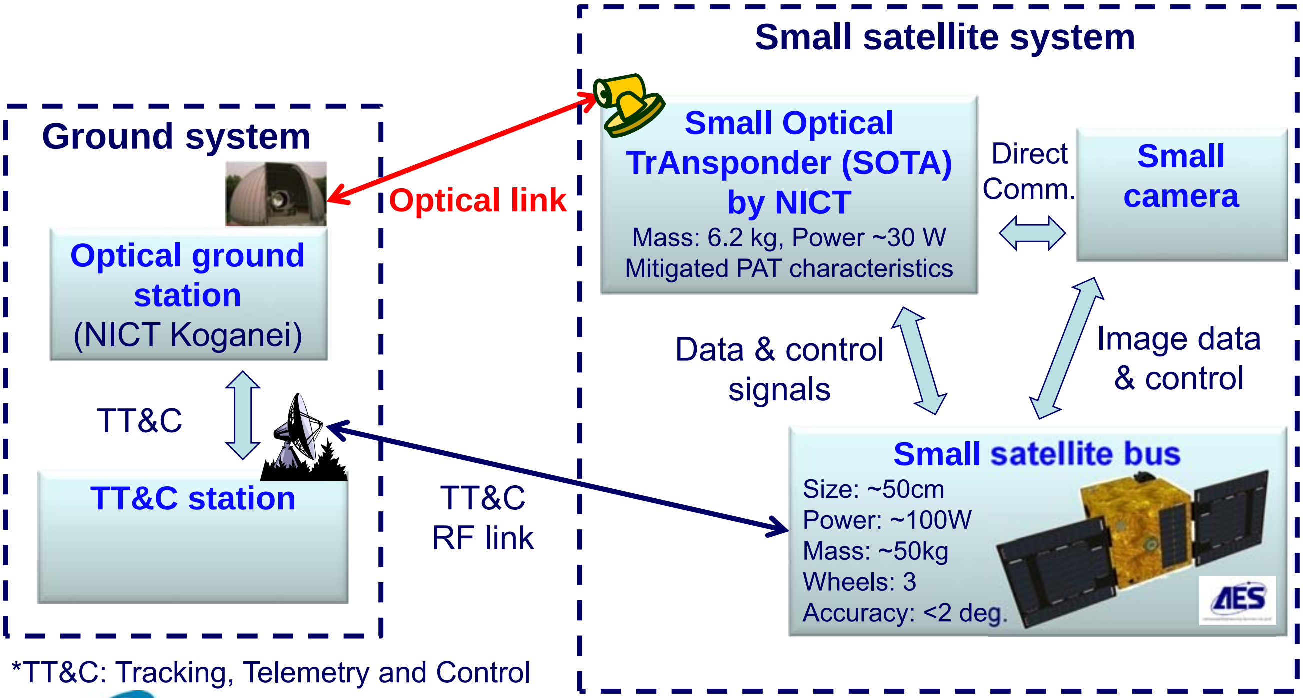
Short term space verification of component level technologies by micro-satellites

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



Short term space verification by micro satellites (2~3 years)

Space Optical Communications Research Advanced Technology Satellite (SOCRATES)



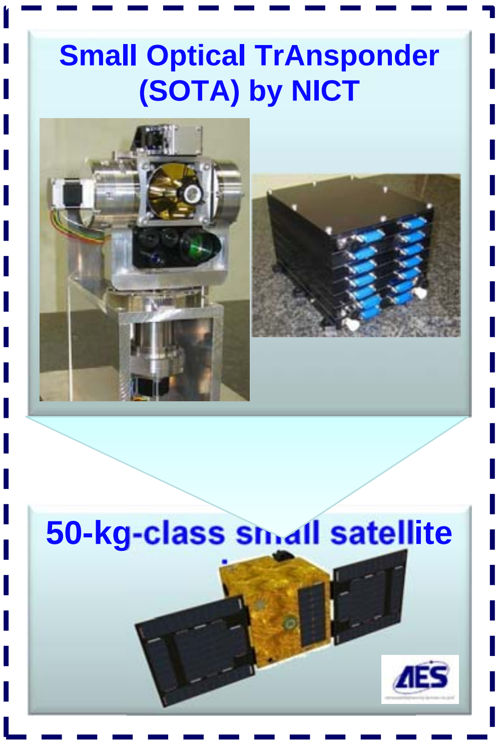
*TT&C: Tracking, Telemetry and Control

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)

Basic experimental items for satellite QKD	
Protocol	Quasi B92
Clock rate	10 MHz
Mean photon number	~0.1 photons/pulse at the OGS
Measurement	
QBER	To be measured
Dark count rate	To be measured



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

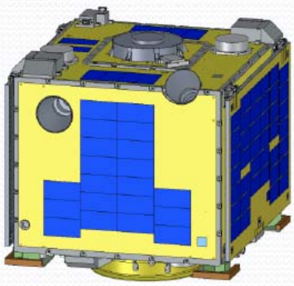
- Demonstrate international scientific missions by inviting instruments from abroad
- Investigation on advanced bus system technologies for future scientific micro-satellites
- Development of a reliable, robust and cost effective micro-satellite bus system

Expected effects

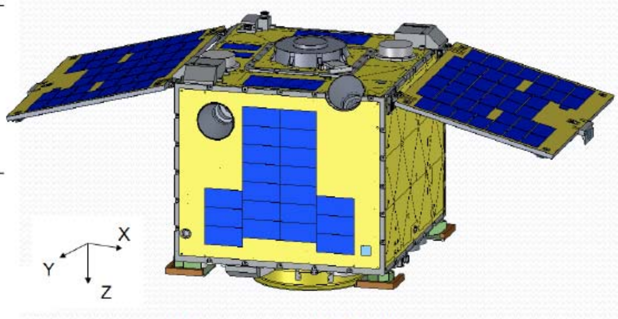
- Realization of mechanism of rapid demonstration of scientific missions in the future
- Improvement of microsatellite technologies which enables future challenging scientific missions
- Commercial spin-off of providing cost-effective microsatellite bus systems

RISESAT System Specifications

Size and weight		
	size	Smaller than W 500 x D 500 x H 500 mm
	weight	Max. 60. Typ. less than 55 kg
Orbit		
	type	Sun Synchronous Orbit
	local time	9:00–15:00 (Default LTDN 11:00)
	altitute	between 500 – 900 km
	inclination	approx. 98 deg
Attitude determination and control		
	method	3-axis stabilization
	pointing accuracy	< 0.1° (3σ) (Reqs.), < 0.04° (3σ) (Objectives)
	pointing stability	6"/s
	sensors	star sensor (2), FOG (3-axes), magnetometer (3-axes), GPS receiver (1), course and accurate sun sensors(4π)
	actuators	reaction wheels (4) magnetic torquers (3-axes)
Power supply		
	solar cells	GaAs multijunction cell 10 series x 5 parallel x 3 panels (Deployanble panels and one body panel) 10 series x 1 parallel + 10 series x 2 parallel
	battery unit	9 series x 2 parallel NiMH (3.7Ah, 18V)
	max. power generation	> 100 W
	max. power consumption	> 50 W
Communication		
	command uplink	UHF, 2400bps at Sendai station, Japan
	HK downlink	S-Band, 0.1W, 38400pbs – max. 500Kbps main: Sendai station, Japan sub: Fukui Univ. of Tech. station, Japan sub: Kiruna station, Sweden
	Mission Data downlink	X-band, max. 2.45Mbps main: Fukui Univ. of Tech. station, Japan sub: Sendai station, Japan



Launch configuration

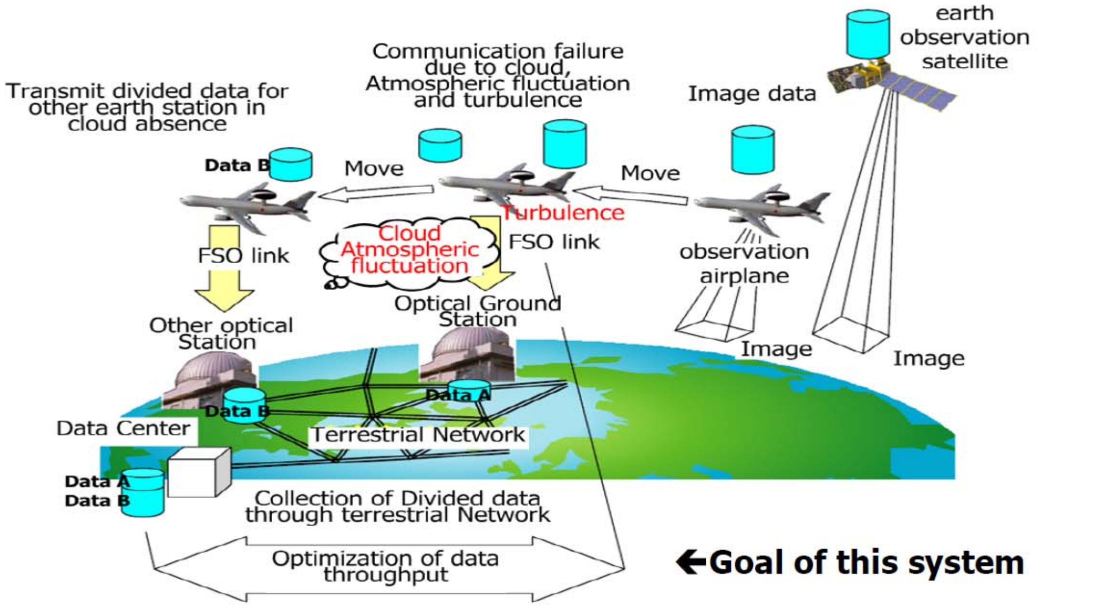


After panel deployment

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.**

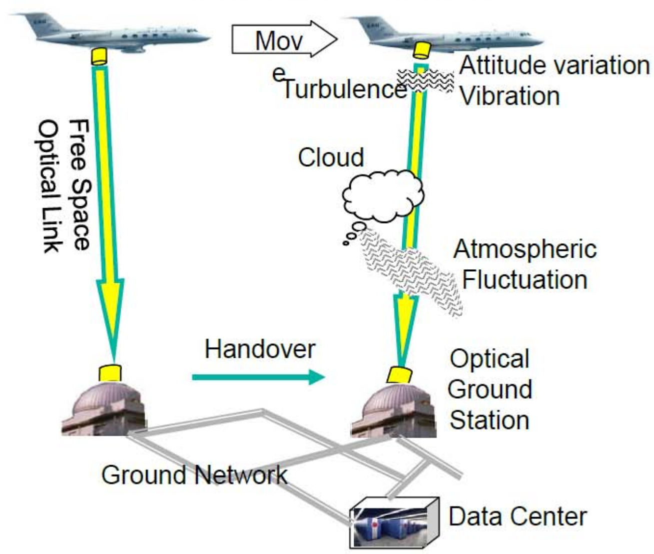


←Goal of this system

Reference: Y.Suzuki, et.al.,"Optical Free Space Communication System for 40Gbps Data Downlink from Satellite/Airplane", 29th AIAA International Communications Satellite Conference, AIAA 2011-8011, December 2011

System Concepts and Key Technology

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.

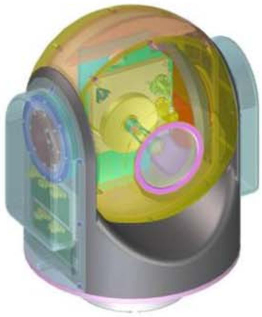
3. Fluctuation of the receved signal caused by the attitude variation and the vibration of the vehicle and atmospheric distortion.

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

Item	Specification
Size	380×420×531mm
Optical I/O Diameter (window)	110mm
AZ-axis Angle Range	±280deg.
EL-axis Angle Range	±115deg.
Moment of Inertia	1.77e-01 $kg \cdot m^2$ (EL) 0.67 $kg \cdot m^2$ (AZ)
Angle Resolution	0.01 deg.
Total Weight	35kg

Outdoor communication link test using the mobile terminal

NEC Confidential

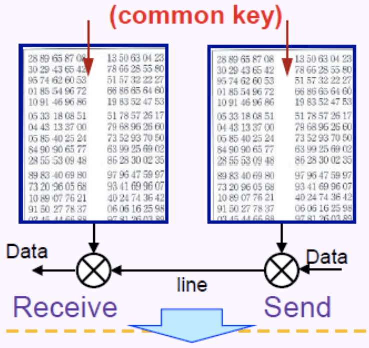
Empowered by Innovation NEC

1. Contraption points of this mission

JAXA

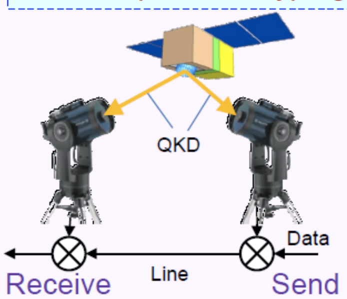
Baseline of quantum cryptography

One-time pad cryptography



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

Basic quantum cryptography

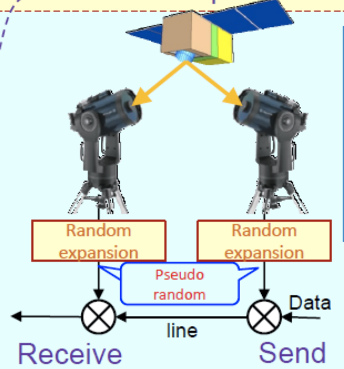


- Unconditional security
- Data rate= QKD rate(very slow)(less than 100kbps (@20dB loss)*)
- All end-users need big facilities(ex.. optical antenna)

* A. R. Dixon, Z. L. Yuan, J. F. Dynes, A. W. Sharpe, and A. J. Shields. Optics Express, Vol. 16, Issue 23, pp. 18790-18979

Contraption points

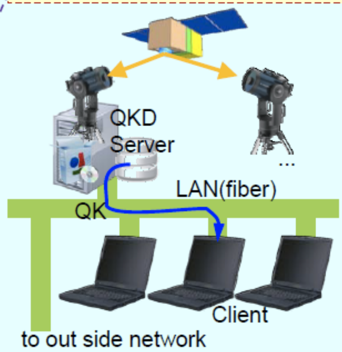
Random expansion



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

These contraptions make a difference in practical use

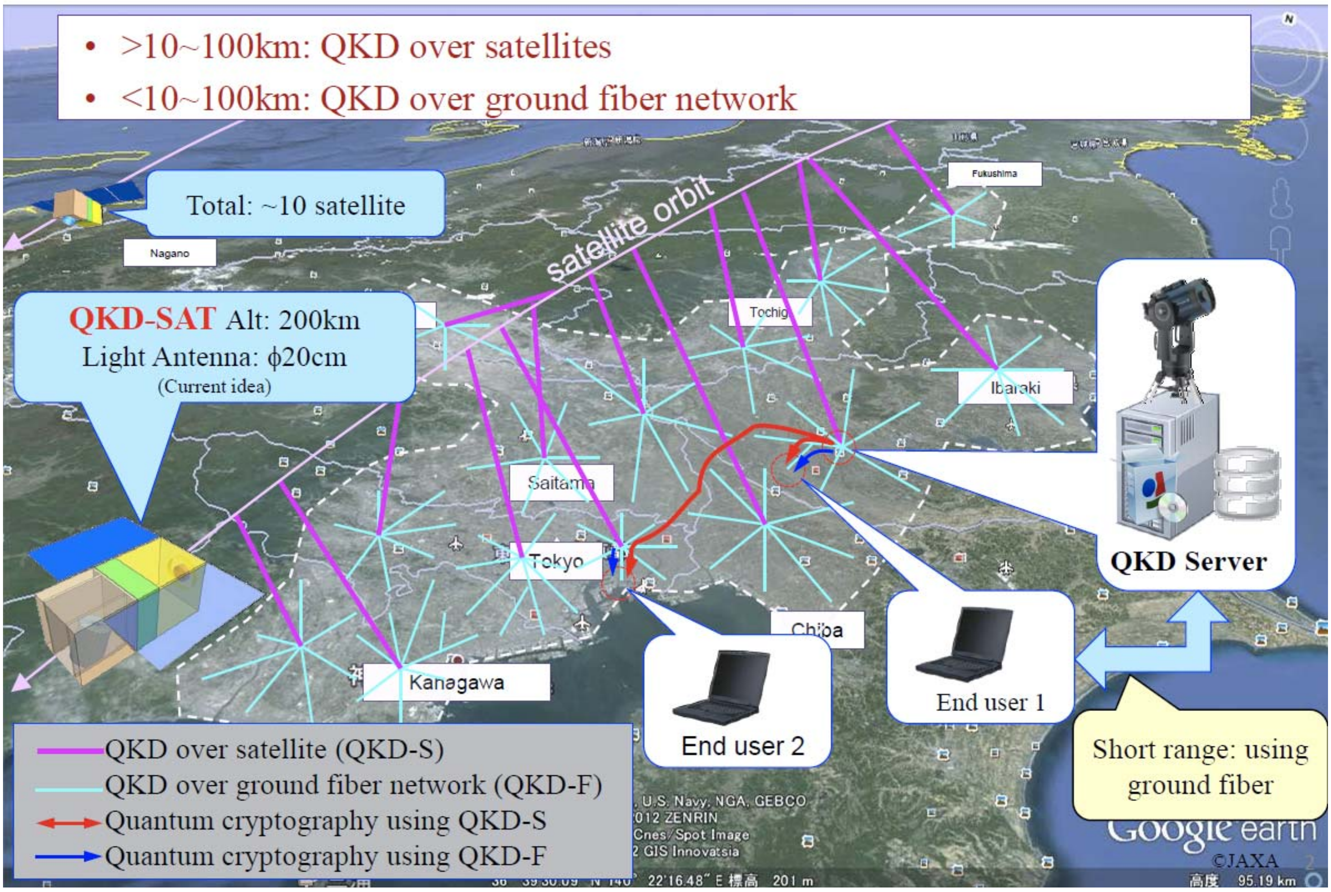
Server-client architecture



- Optical Ground Stations are shared (small load for end users)
- Ground fiber network is used to short range QKD

©JAXA

2. Total System Image (in future actual use phase)

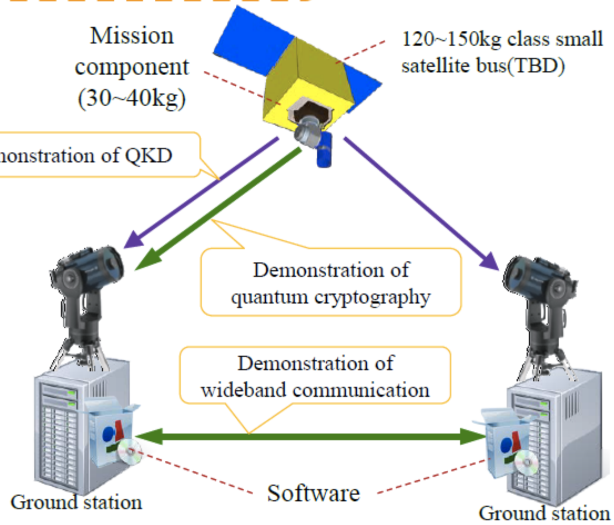


3. Plan for Flight Demonstration

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.

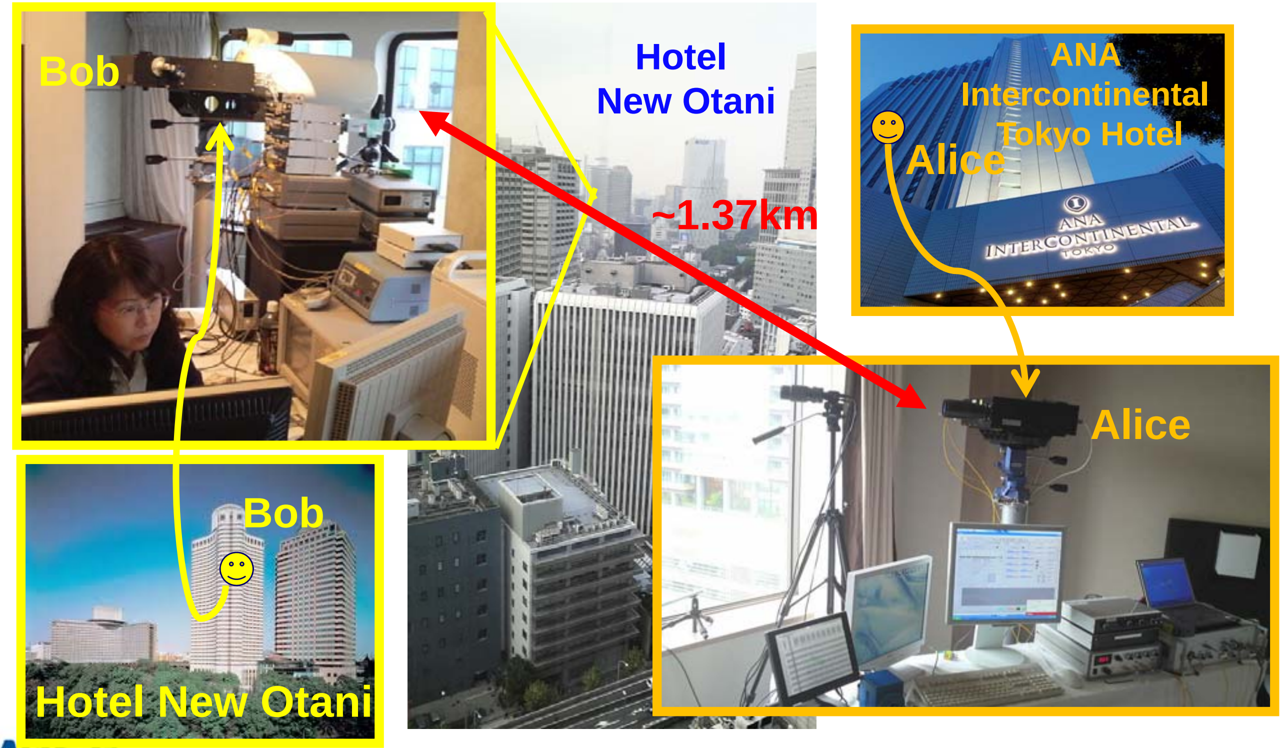


Overall Plan

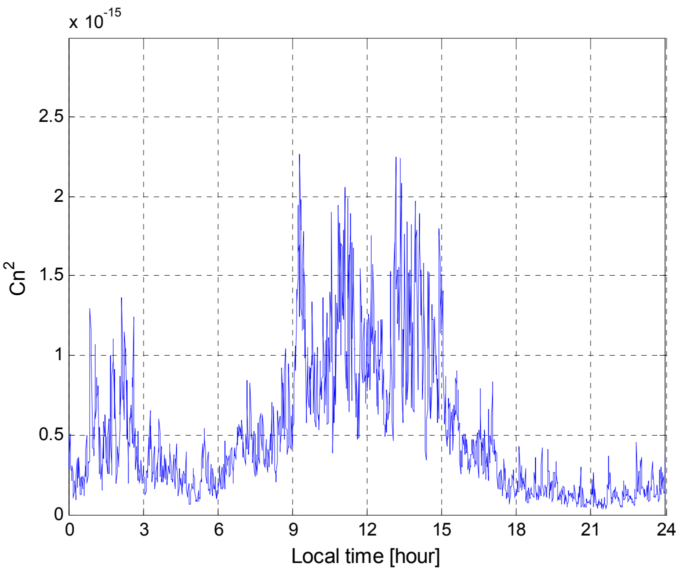
	FY2011	FY2012	FY2013	FY2014	FY2015	2016	2017~
Study Phase	Basic Study	System Study					
Development and Demonstration Phase				Development phase			Flight Demonstration

(Tentative)

Live demo: Free-space laser communication and QKD experiments in UQCC conference



Measurement of Cn^2 between two buildings



Distance : 1.35km, Height of the link : 138m

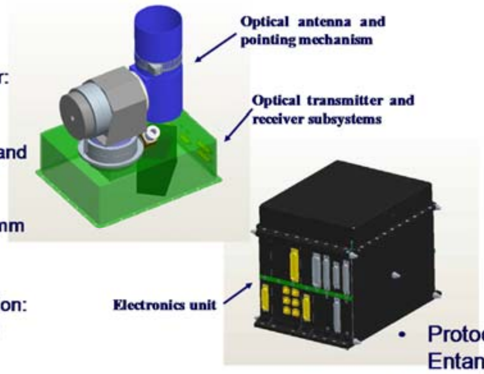
Scintillometer (Tx)

Scintillometer (Rx)

Conceptual designs for satellite QKD

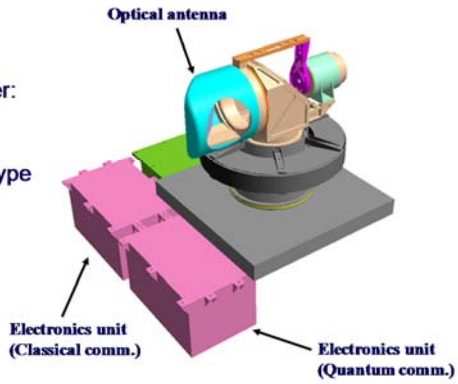
Terminal model 1: WCP + decoy

- Protocol: WCP+decoy
- Antenna diameter: 125 mmϕ
- Antenna type: Cassegrain type and coude path
- Size: 305 x 390 x 125 mm
- Mass: 46 kg
- Power consumption: 97.4 W (nominal) 138 W (peak)

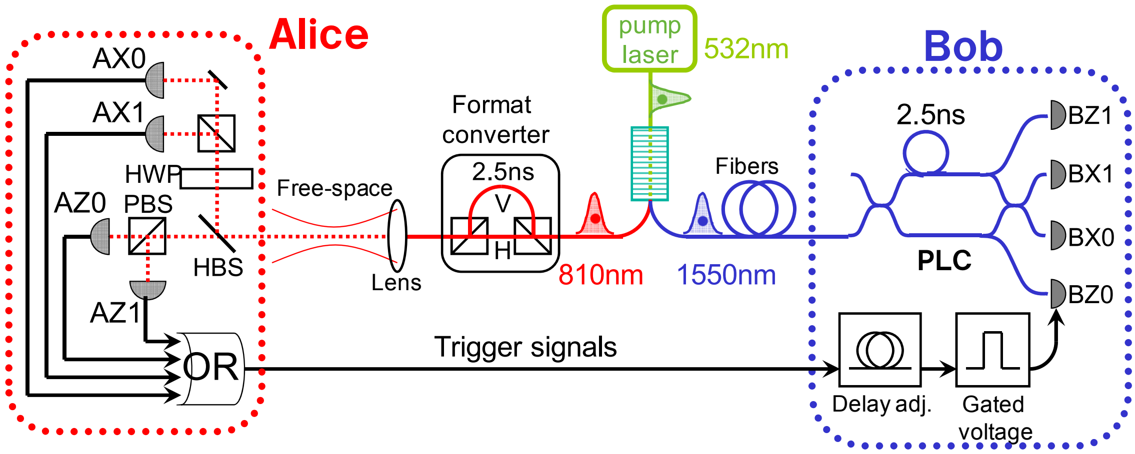


Terminal model 2: Entanglement (E91)

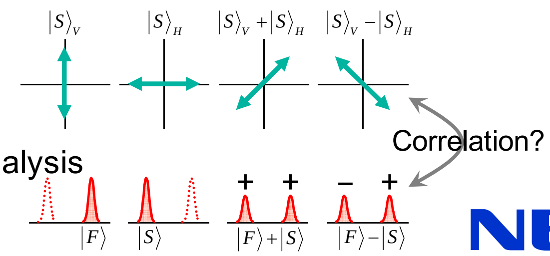
- Protocol: Entanglement (E91)
- Optical antenna diameter: 100 mmϕ
- Antenna type: Cassegrain and Elbow type
- Size: 400 x 250 x 500 mm
- Mass: 37.5 kg
- Power consumption: 119.7 W



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)

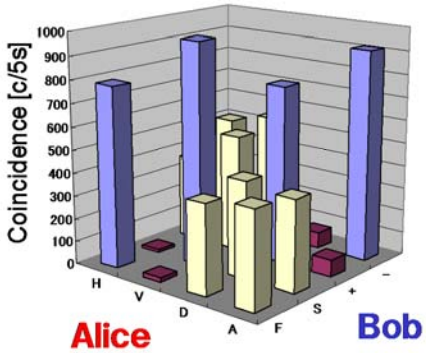


Coincidence results

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 ~720bps

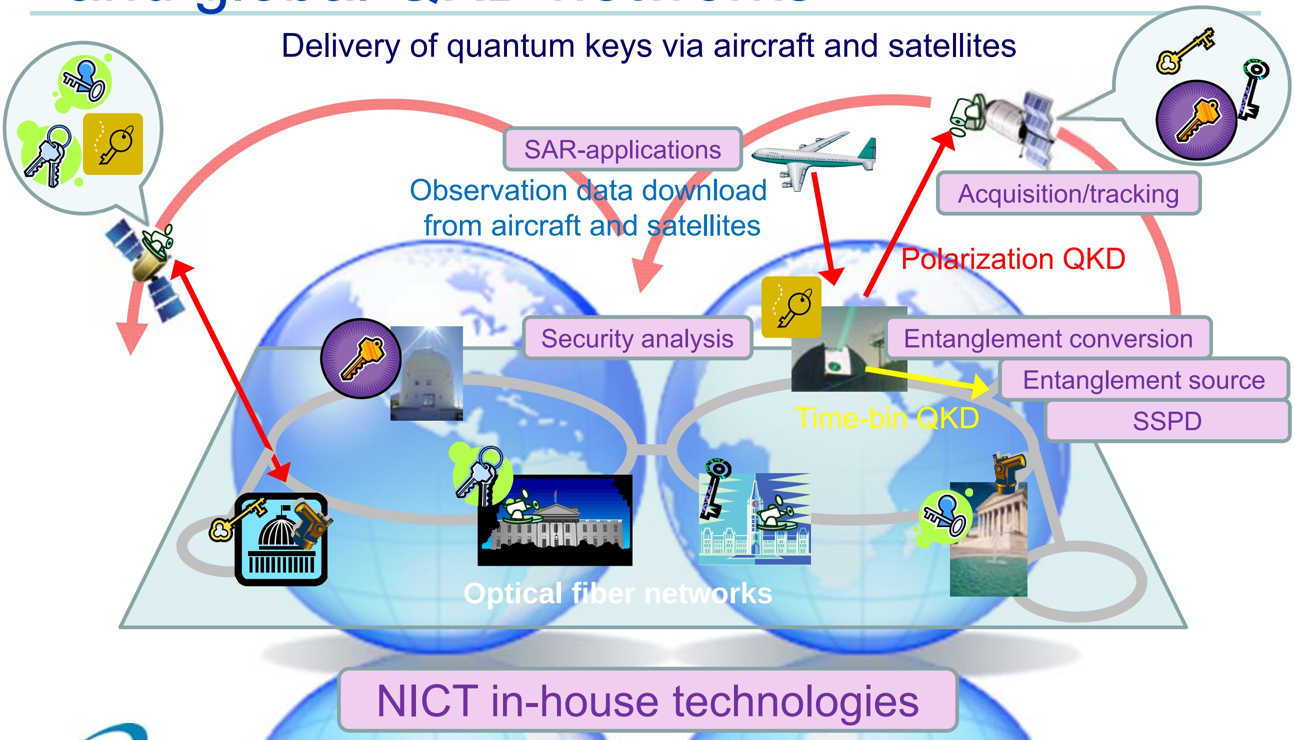
Error rate

- 4.8 %

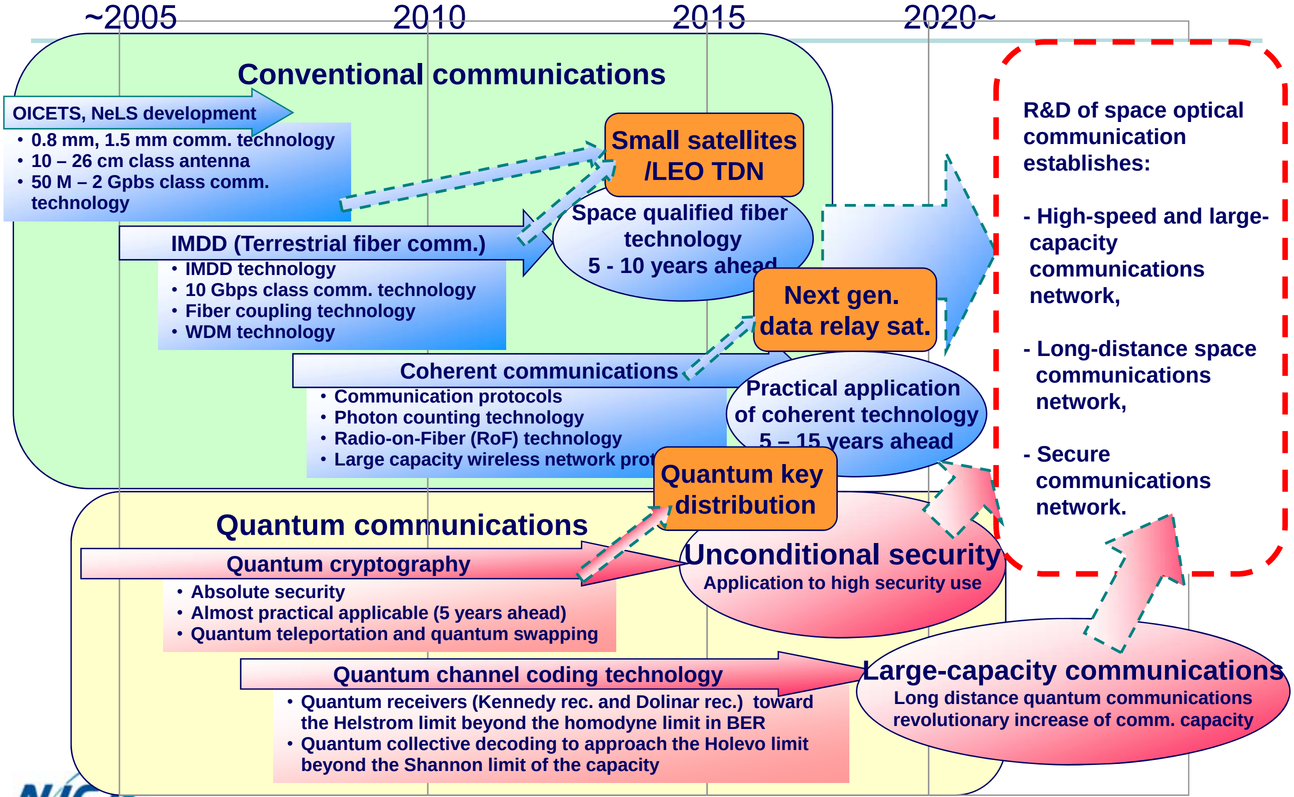
Fujiwara, et al., APL95, 261103 (2009).
Yoshino, et. al,. Technical Report of QIT (2010)

High speed laser communication links and global QKD networks

Delivery of quantum keys via aircraft and satellites



R&D load map for space optical communications



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.