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RSS-Hydro, S.à r.l.-S

A Comparison Between Conventional Earth Observation Satellites and CubeSats: Requirements, Capabilities and Data Quality

Dietmar Backes[1], Saif Alislam Hassani [1], Guy Schumann [2,3] and Felix Norman Teferle [1]

[1] Geodesy and Geospatial Engineering, RUES, University of Luxembourg, Luxembourg

[2] RSS-Hydro Sarl-S, Dudelange, Luxembourg

[3] School of Geographical Sciences, University of Bristol, United Kingdom

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Content:

- Optical Earth Observations (EO) from Lower Earth Orbit (LEO)
- Some Principles of Optical Spaceborne Imaging
- Conventional Satellites vs. CubeSats
- Practical Examples
- Summary and Outlook

Earth Observation Applications

Disasters:

- Volcano and wild fire
- Flooding
- Monitoring geo hazards
- Deformation monitoring

Environmental Monitoring:

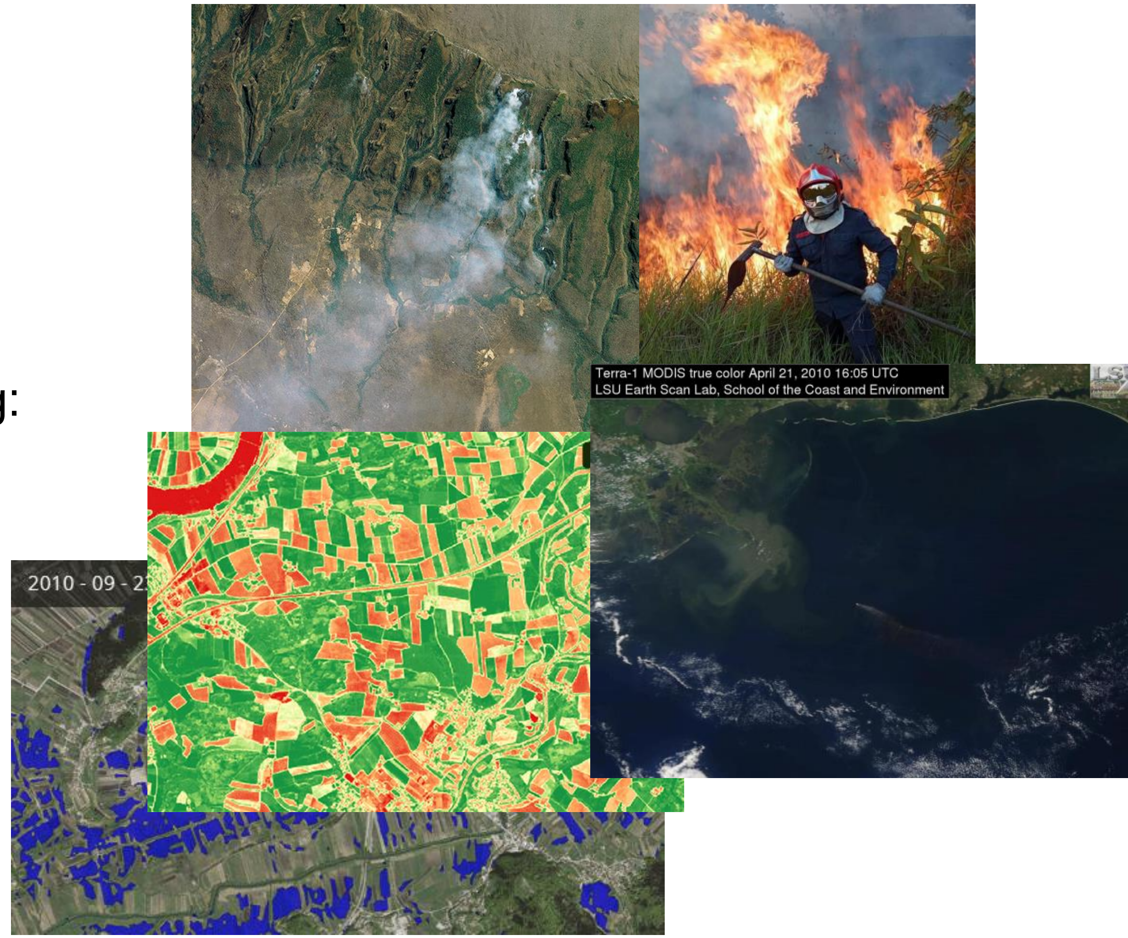
- Water quality
- Pollution, oil spills etc.

Farming and agriculture:

- Crop monitoring
- Forest monitoring

Mapping

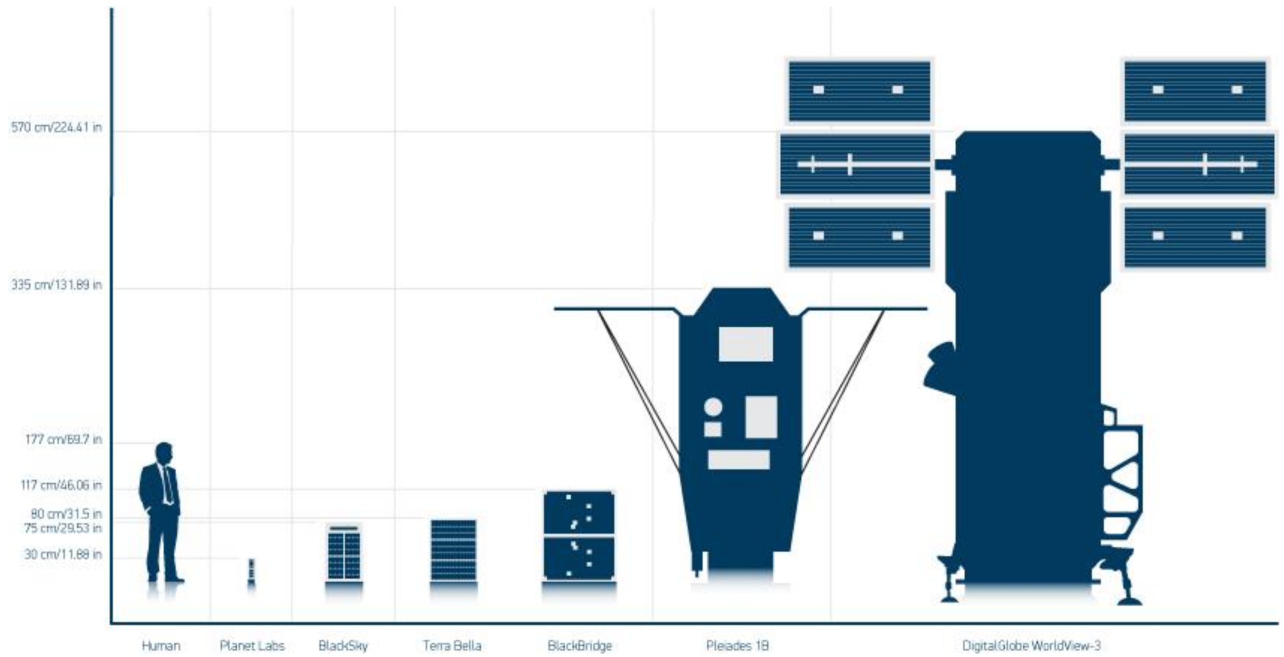
- Topographic mapping



Credit: Sentinel-hub

etc.

Conventional EO Satellites vs. CubeSats



Credit: Digital Globe 12/2016

…so where are the differences?

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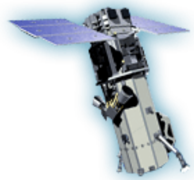
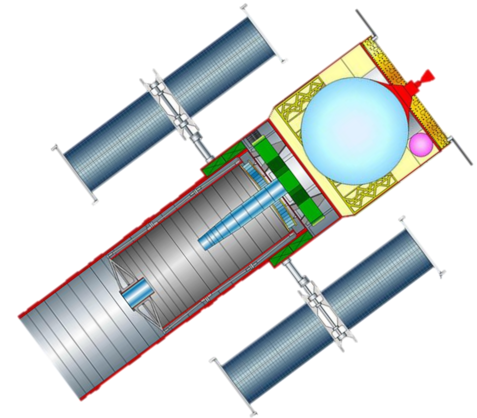
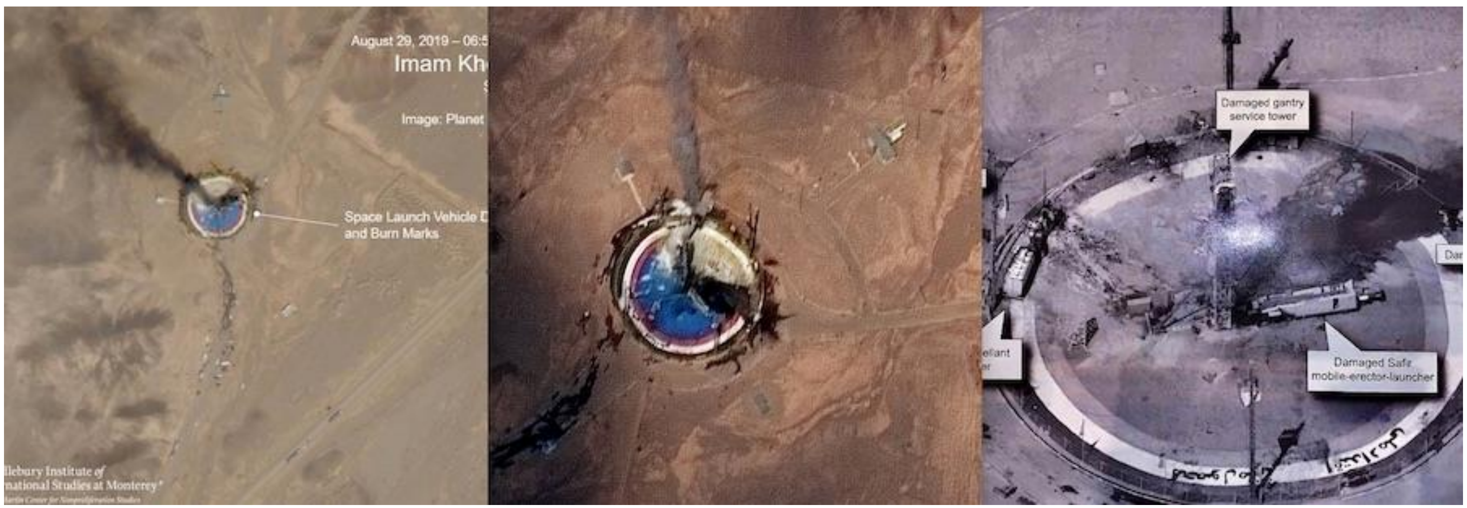
Pictures from Space





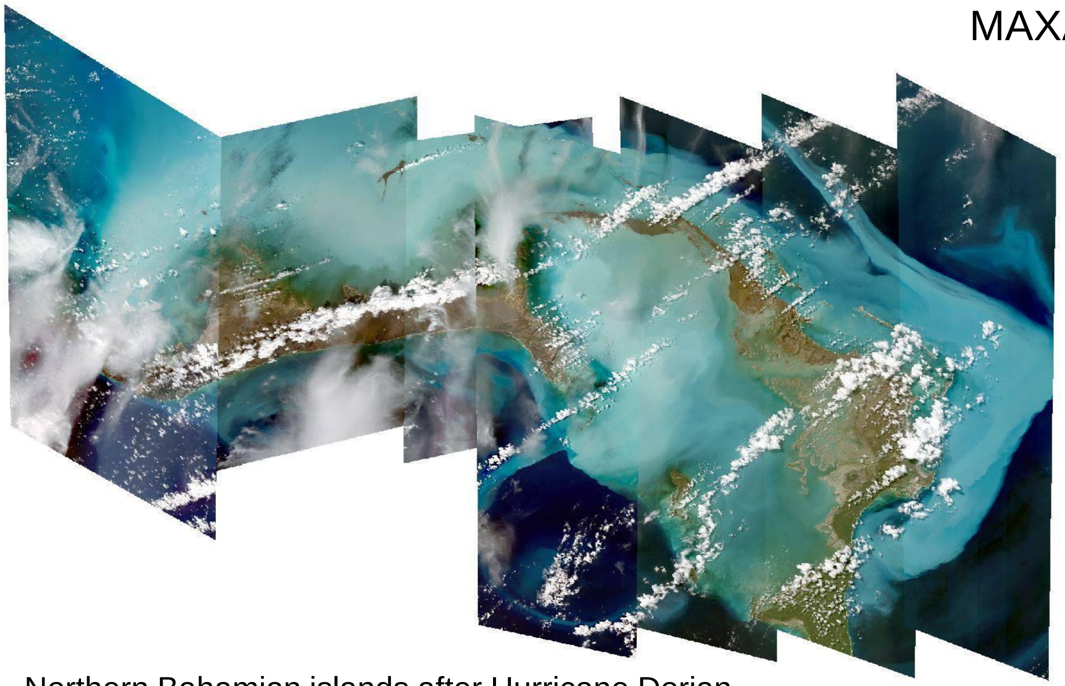


Spaceflight now 30/08/2019, Images of Semnan launch site Credit: Planet, Maxar and @realDonaldTrump

- Left: captured by Planet approx. 3m resolution (Dove, RapidEye or Skysat)
- Centre: Maxar/Digital Globe WorldView2 Satellite approx. 0.3m resolution
- Right: US intelligence image https://twitter.com/realDonaldTrump/status/1167493371973255170
  suspected KH11 type satellite (USA-244)

Very High-resolution Images by WorldView

MAXAR



Northern Bahamian islands after Hurricane Dorian

WorldView 2 Satellite

- Multispectral images captured from a single orbit
- 29,900 km2 in 7 separate scenes

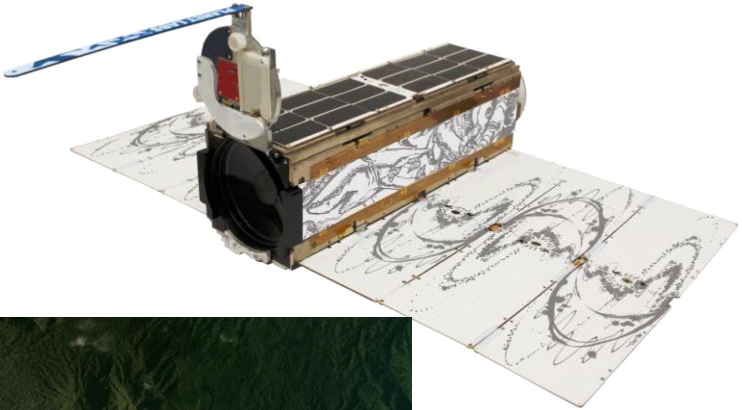
- Highly agile: body-pointing range of ±40º correspondent to 1355km FOR cross-track
- Pointing accuracy <500 m at image start and stop
- Large 2.2 TB on-board storage;
- Imagery is downlinked in X-band at 800 Mbit/s
- Theoretical 1.1 day revisit time

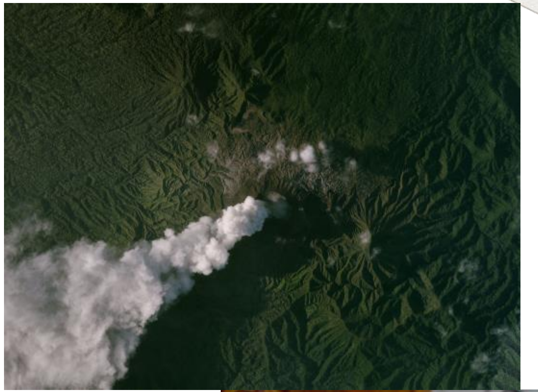
High-resolution Optical Images from CubeSats

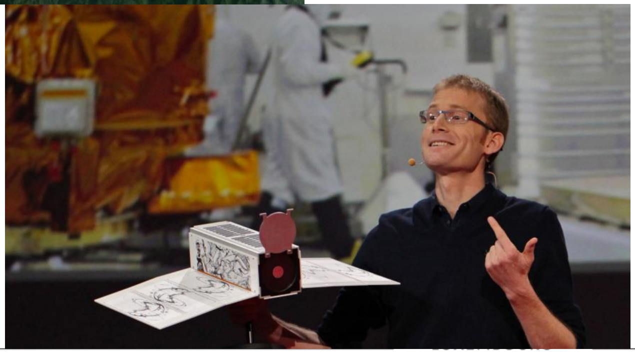
Table 2
Preliminary assessment of the feasibility of Cubesat-based missions carrying different remote sensing technologies.

Technology	Feasibility assessment (feasible/problematic/infeasible)	Justification
Atmospheric chemistry instruments	**Problematic**	Low sensitivity in SWIR-MIR because of limited cooling capability
Atmospheric temperature and humidity sounders	**Feasible**	e.g., GNSS radio occultation, hyperspectral millimeter-wave sounding
Cloud profile and rain radars	**Infeasible**	Dimensions, power
Earth radiation budget radiometers	**Feasible**	[63]
Gravity instruments	**Feasible**	[64]
High resolution optical imagers	**Infeasible**	Not enough resolution-swath, because limited space for optics and detectors
Imaging microwave radars	**Infeasible**	Limited power
Imaging multi-spectral radiometers (vis/IR)	**Problematic**	Limited imaging capability
Imaging multi-spectral radiometers (passive microwave)	**Problematic**	Limited imaging capability
Lidars	**Infeasible**	Limited power
Lightning imagers	**Feasible**	[30]
Magnetic field instruments	**Feasible**	[65]
Multiple direction/polarization radiometers	**Problematic**	Limited dimensions for receiver electronics
Ocean color instruments	**Feasible**	[4]
Precision orbit	**Feasible**	[66]
Radar altimeters	**Infeasible**	Dimensions
Scatterometers	**Infeasible**	Dimensions

Selva, D., Krejci, D., 2012. A survey and assessment of the capabilities of Cubesats for Earth observation. Acta Astronaut. 74, 50–68. https://doi.org/10.1016/j.actaastro.2011.12.014



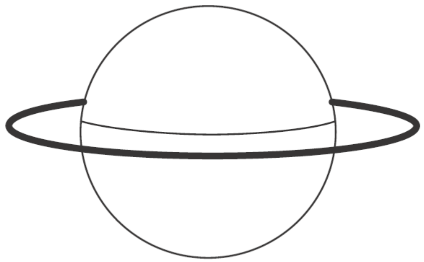




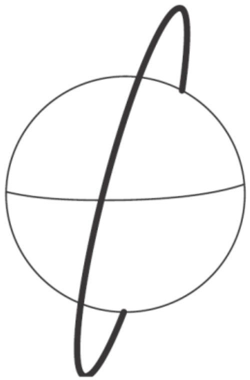
Low Earth Orbits (LEO)

- Basic principle:
  a) Equatorial obit
    - Uncommon for conventional EO

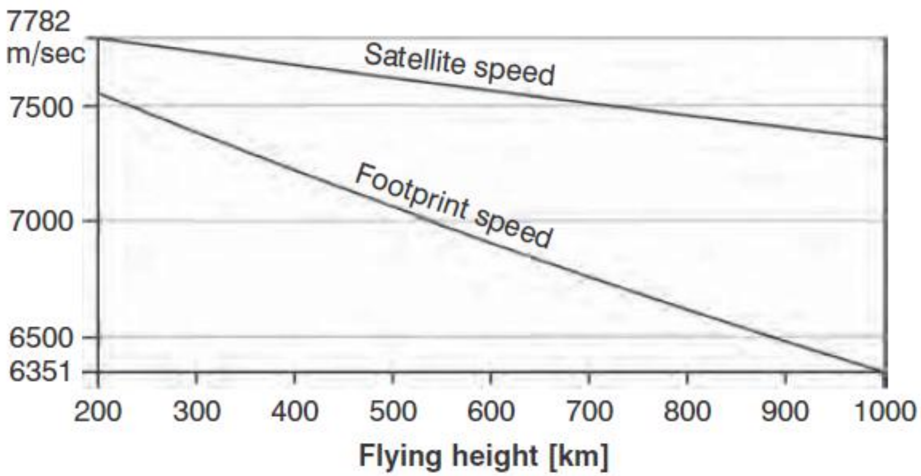
  b) Sun-synchronous, near-polar orbit with 98° inclination
    - most common orbit for optical EO satellites
    - orbit period approx. 90 min at 700-800km
- Satellite Speed as a function of flying height in a circular orbit:
  - Approx. 7 km/s for EO satellites
  - t_{dwell} (1m GSD) ~ 0.14msec
  - $t_{int} < t_{dwell}$



A



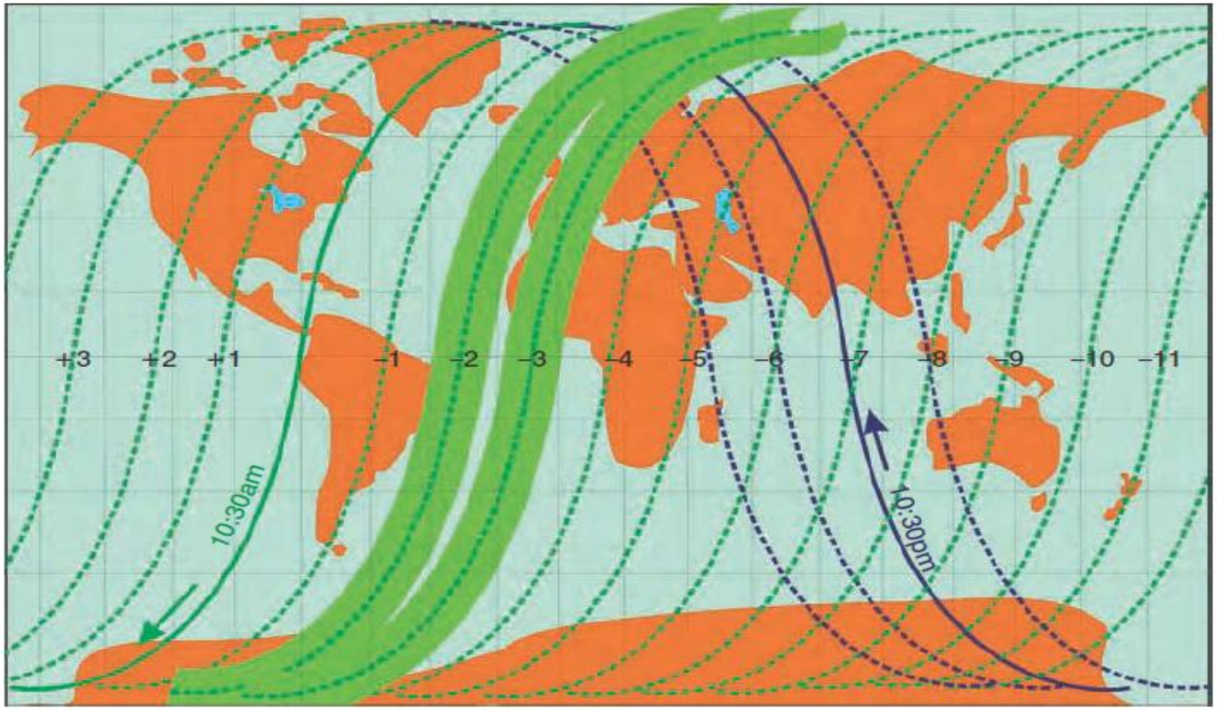
B



Low Earth Orbits (LEO)

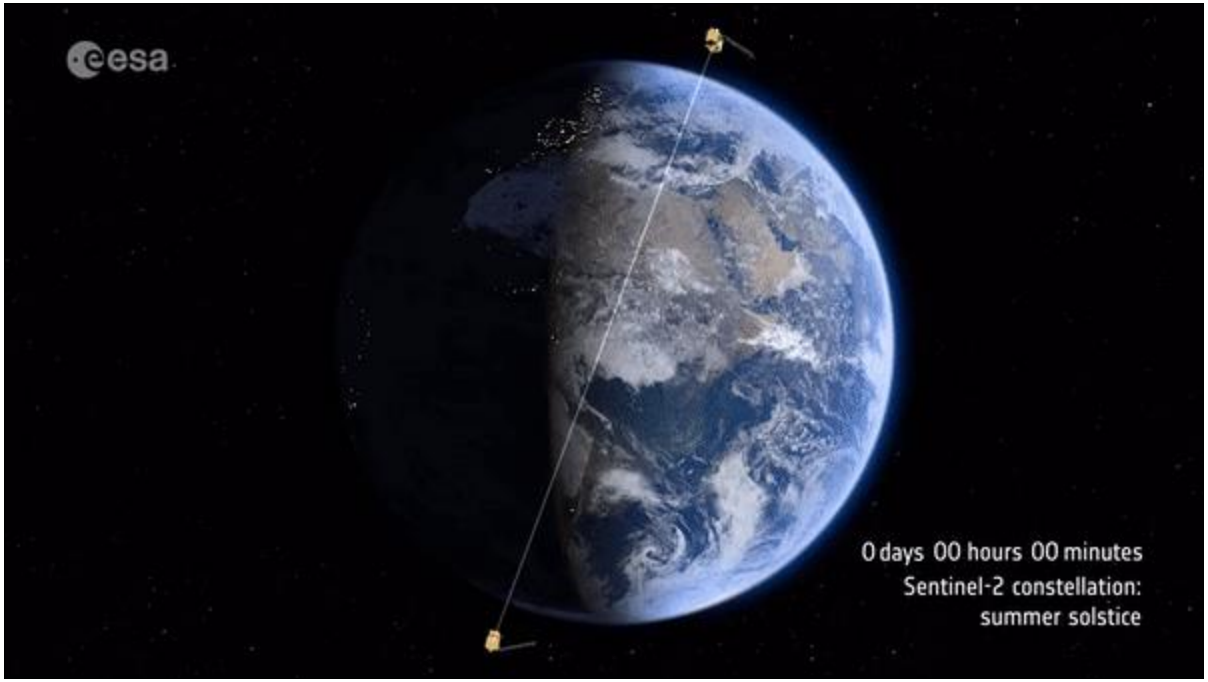
- Example Ikonos2 (typical for EO satellites)
  - Inclination: 98.1°
  - Period: 97 min
  - Equatorial crossing: 10:30 am solar time
  - Altitude: 681km

Satellite speed: 7.613 km/s
Footprint speed: 6.878 km/s

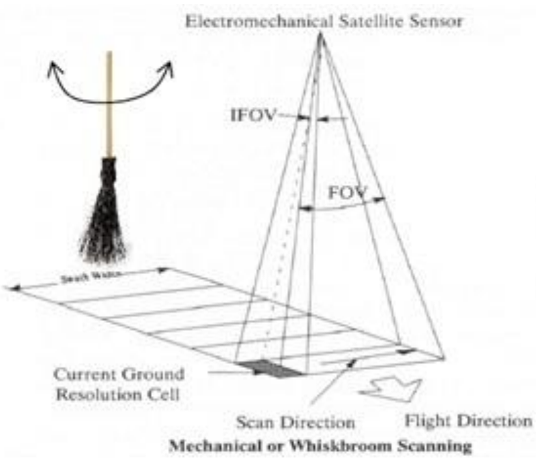


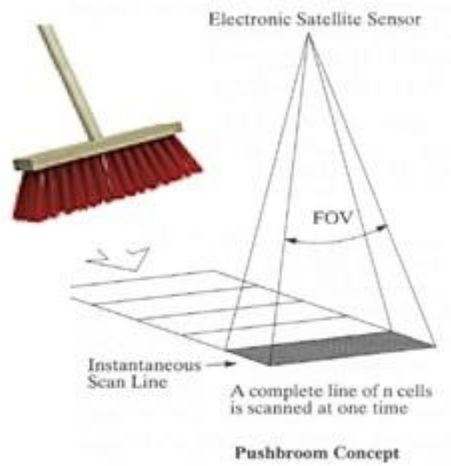
Low Earth Orbits (LEO)

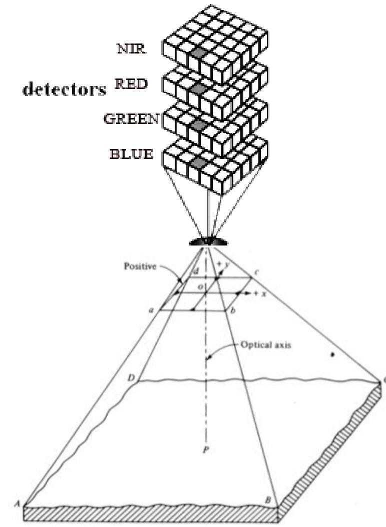
- Revisit time:
  - is a function of swath width, spacecraft agility/pointability and the number of space crafts
  - Often called ‘temporal resolution’



Principles of Imaging Sensors





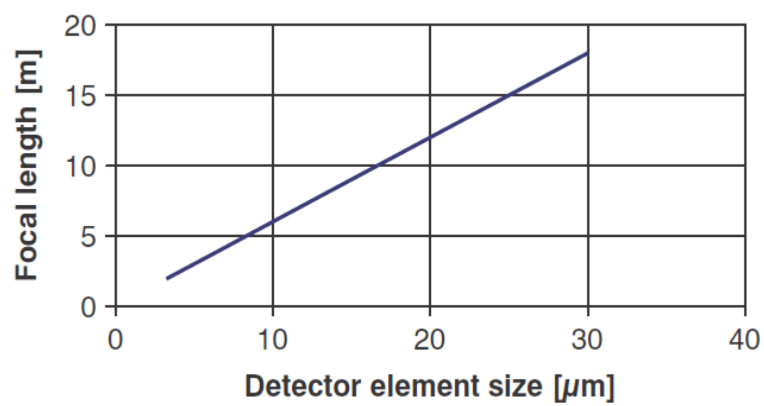


Staring, frame Geometry

Relationship between detector element, focal length, orbit height and GSD:

$$f = \frac{H_{Orbit}}{GSD} \cdot x$$

The figure shows the relationship between required focal length and detector size for a orbit altitude of 600km at 1m GSD.



Important Requirements for Spaceborne Imaging Systems:

- Spatial resolutions and quality:

$$MTF_{SR} = MTF_{Optics} \cdot MTF_D \cdot MTF_{PS}$$

- Radiometric aspects:
  - Higher resolution means smaller amounts of energy from smaller ground pixels
  - ***Time related*** factor: dwell time (t_{dwell}) and ***geometry related*** factor (IFOV)
  - E.g. the reduction of 10m to 1m GSD reduce the amount of energy at the detector by approx. 1000.

- Pointing accuracy:
  - Start and stop pointing: < 500m
  - Geolocation accuracy: 6.5m

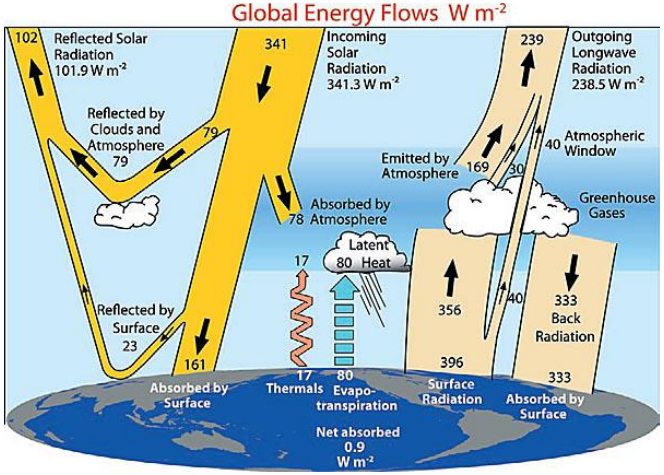
  Common specification for high-resolutions EO systems

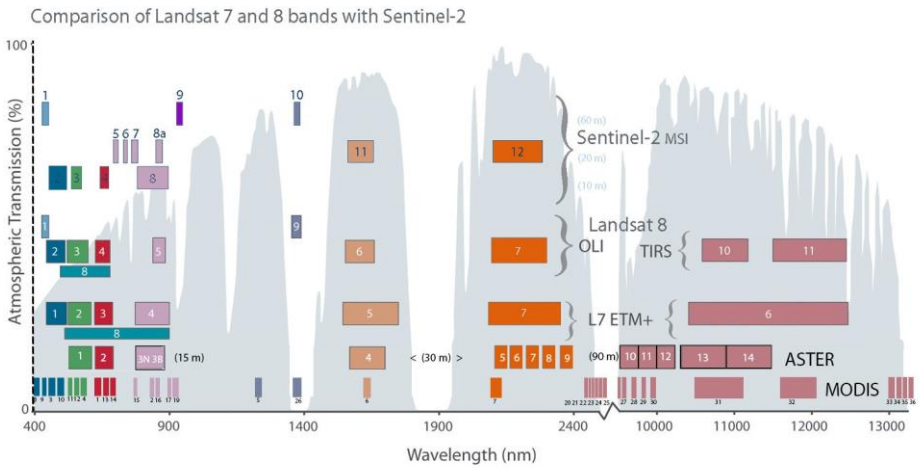
- Platform stability:

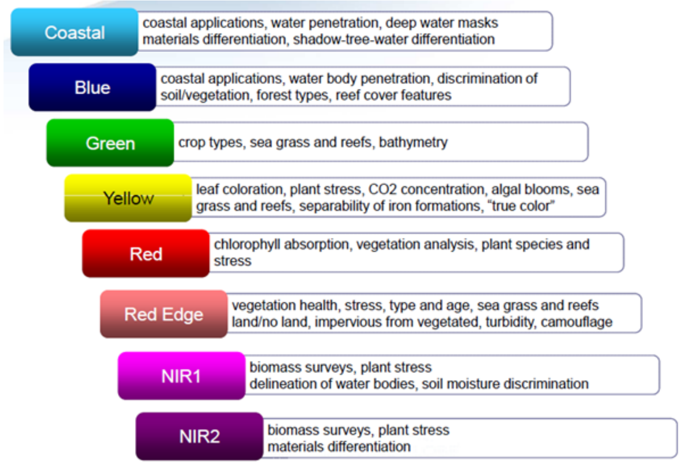
$$MTF_{PS} = MTF_{LM} \cdot MTF_J \cdot MTF_{sin}$$

Resolutions

- Temporal resolution/revisit time
- Geometric or spatial resolution
- Spectral resolution:
  - Multispectral, Hyperspectral
  - Visual, NIR, SWIR and TIR
- Radiometric resolution
  - 10 -11 bit

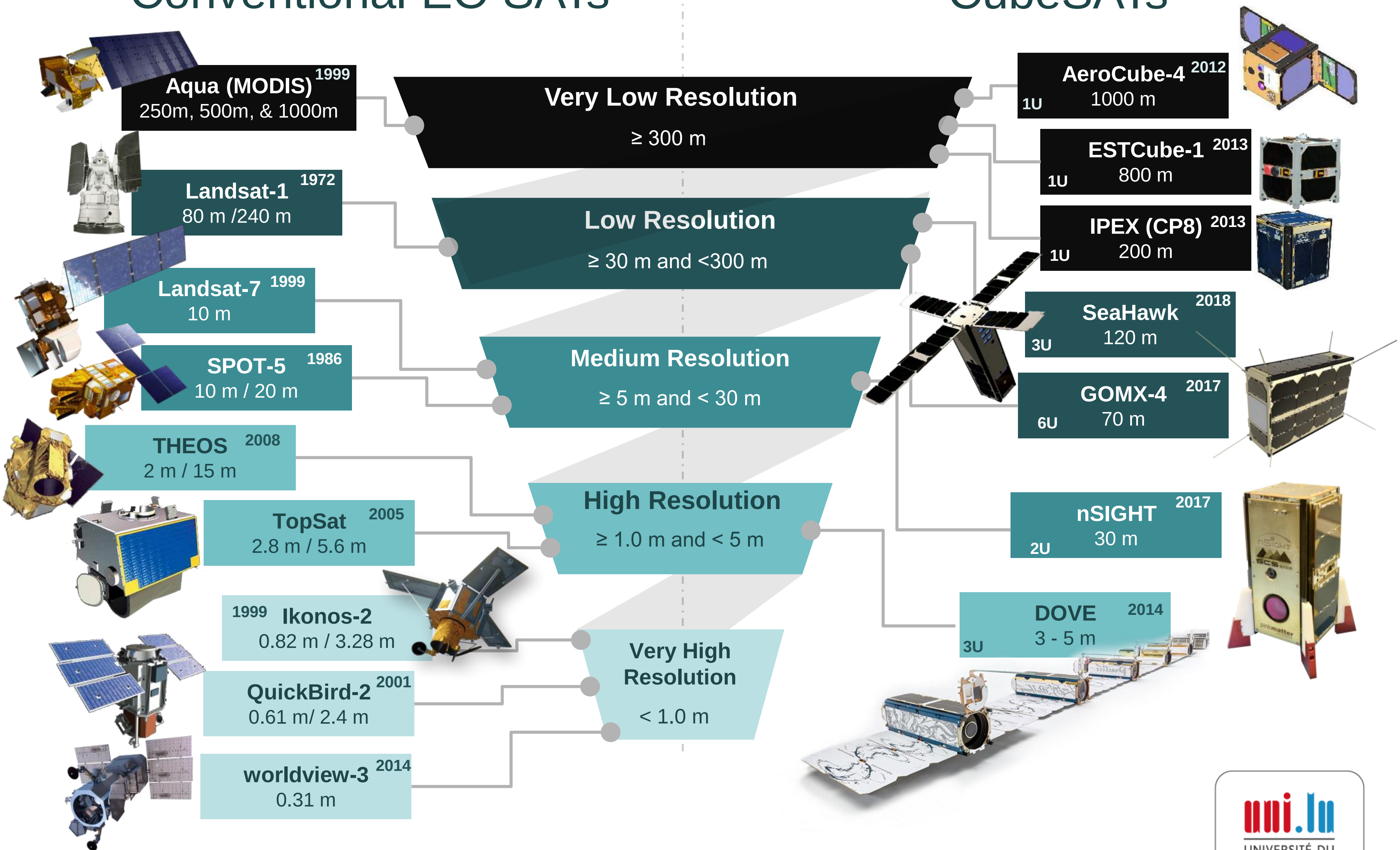






Conventional EO SATs

CubeSATs

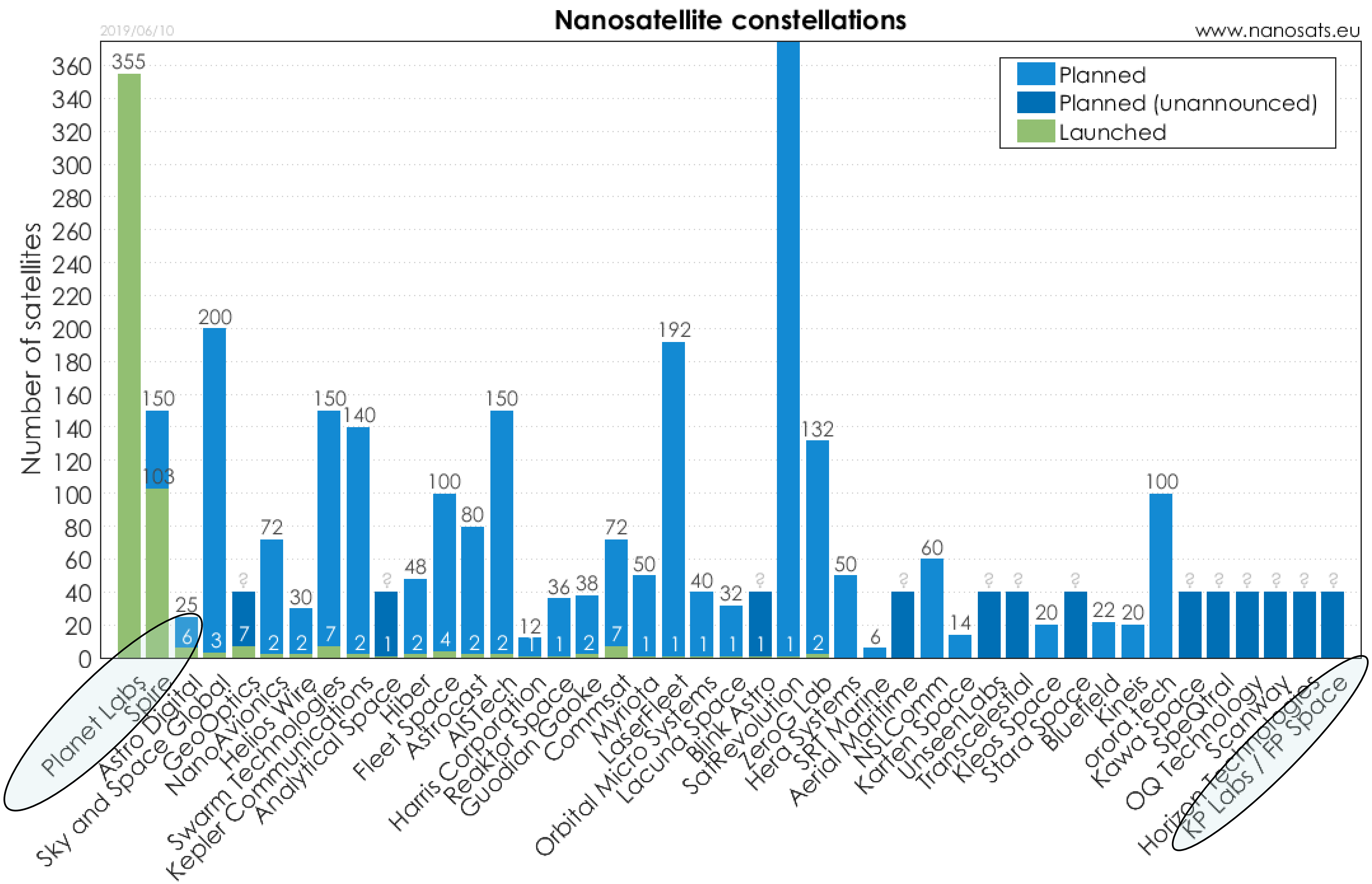


Evolution of Optical EO Satellites:

Launch Date	Organisation	Mission		Orbit	GSD	Sensor(s)	Pointing capability/Agility
1972 - 2013	NASA	Landsat	Landsat 1-3	907 to 915 km, 99˚	80m	Multi spectral Scanner (MSS)	Up to 10.3º off nadi
			Landsat 4-5	705 km, 98.2˚	30m	Thematic Mapper (TM)	
			Landsat 7		30m	Enhanced Thematic Mapper Plus (ETM+) 8-band whiskbroom scanning radiometer	Up to 7.5º off nadir
			Landsat 8		30m	Operational Land Imager (OLI) similar spectral bands to the ETM+	Up to 7.5º off nadir
1998-03-24	CNES (Centre national d'études spatiales)	Spot 1- 4		832 km, 98.8˚	10 PAN / 20 MS	High-Resolution Visible and Infrared sensor (HRV IR)	± 27˚
1999-09-24	Space Imaging/ GeoEye Inc.	Ikonos-2		681 to 709 km, 98.1˚	1 m PAN (0.82 m at nadir), 4 m MS (3.2 m at nadir)	Kodak Optical Sensor Assembly (OSA) Pushbroom detector	±30º
1999-12-18	NASA	Terra	ASTER	705 km	15 m VNIR 30 m SWIR 90 m TIR 15 m Stereo	Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 14 bands	0˚ / 27˚
2002-05-04			MODIS	705 km	250 m (bands 1–2) 500 m (bands 3–7) 1000 m (bands 8–36)	Moderate Resolution Imaging Spectroradiometer (MODIS) Medium-resolution, multi-spectral, cross-track scanning radiometer 36 spectral bands	
2001-10-18	DigitalGlobe Inc	QuickBird-2		450 km, 97.2˚	0.61 m (PAN) and at 2.4 m (MS)	Ball Global Imaging System 2000 (BGIS 2000) Pushbroom array	±30º
2002-05-04	CNES (Centre national d'études spatiales)	Spot-5		832 km, 98.7˚	5m (single) 3.5m (double) PAN / 10m MS	High Resolution Geometric (HRG) High Resolution Stereo (HRS)	± 27˚ HRG ± 20˚ HRS
2008-08-29	RapidEye/Planet	RapidEye		630 km, 98˚	6.5 m	Jena-Optronik RapidEye Earth Imaging System (REIS) Multispectral pushbroom sensor 5 spectral bands	±20˚
2013-11-21	Skybox/Terra Bella/Planet	SkySat		600 km, 97.8˚	90 cm PAN / 2.0 m MS	CMOS frame detectors (30f/s video from space)	
2014-08-13	DigitalGlobe Inc/MAXAR	WorldView-3		617 km	0.31 m PAN 1.24 m MS 3.7 m SWIR	Panchromatic, 8 Multispectral and 8 SWIR bands	±40º (nominal in any direction)
2015-06-23	ESA and EU (European Commission - Copernicus)	Sentinel-2 (a, b)		786 km, 98.5˚	10 m: (VNIR) B2, B3, B4, B8 (4 bands) 20 m: B5, B6, B7, B8a, B11, B12 (6 bands) 60 m: B1, B9, B10 (3 bands)	Multispectral Imager (MSI) 13 bands VNIR + SWIR	

information: eo Portal Directory

Some Planned and Launched CubeSat Missions



CubeSat Missions

	Launch Date	Organisation	Mission	Orbit	GSD	Sensor(s)	Resolution	Agility and Positioning
1U	2012-02-13	Budapest University of Technology and Economics	**MO-72 (Masat-1)**	310 x 1450 km, 69.5 deg	1 km / 10 km	VGA camera	640 x 480 pixels	3-Axis gyroscope sensors, 3-Axis magnetometers and 3-Axis accelerometers a semi-active attitude control system based on permanent magnets, hysteresis materials and electromagnets (2-axis)
1U	2012-09-13	The Aerospace Corporation	**AeroCube-4**	470 x 780 km, 64.7 deg	1 km / 10 km	CCDs	3 cameras 1600 x 1200 One Fisheye Lens	
1U	2013-05-07	University of Tartu	**ESTCube-1**	660 km, 98.1 deg, SSO	800 m	Aptina MT9V011 image sensor	640 × 480 pixels. 262 arcseconds per pixel. 4.4 mm telecentric lens a standard M12x0.5 thread 9 mm aperture a depth of field of 0.4 to ∞ m	a field of view of 46 × 35 degrees
1U	2013-12-06	California Polytechnic State University	**IPEX**	460 x 890 km, 120.5 deg	200 m	Five Omnivision OV3642 cameras	2048 x 1536 8-bit compression data lens size: 1/4” pixel size: 1.75 µm x 1.75 µm	
1U	2018-12-05	Aarhus University (Built by Gomspace)	**Delphini-1**	400 km, 51.6 deg, ISS		1U-NanoEye		
1U		GomSpace	**NanoCam C1U (camera name)**		260m, 60m, and 30m		8 mm lens: <260 m/pixel from 650 km 35 mm lens: <60 m/pixel from 650 km 70 mm lens: <30 m/pixel from 650 km 400-750 nm spectral transmission	
2U	2017-04-18	SCS-Space	**nSIGHT**	400 km, 51.6 deg, ISS	30 m	SCS Gecko Imager	Focal length: 70 mm Image Sensor: 2.2 Megapixel RGB Rad. tolerance: Tested to 30 krad TID	

CubeSat Missions

	Launch Date	Organisation	Mission	Orbit	GSD	Sensor(s)	Resolution	Agility and Positioning
3U	2014 - 20XX	Planet Labs	**Dove (Flock-xx xx)**	400, 500, 600 (most are 500km)	3 - 5m	?		
3U	2015-12-16	Microspace Rapid Pte Ltd.	**Athenoxat-1**	540 km, 15 deg	Global view resolution: 1km Wide Angle resolution: 50m to 300m Narrow Beam Resolution: 1m to 20m	?	f/2 to f/10 Optics speed 2.5 deg narrow beam aperture Visible/IR, multiband, hyperspectral Spectrum up to 30Hz Video Refresh	ACS air-coil magnetorquers primarily for stabilization ADS sensors: coarse sun sensors, magnetometer & gyroscopes CDH & ADCS software including Nadir vector determination & payloads drivers
3U	2016-09-26	UK Space Agency	**ALSAT-Nano**	680 km, 98.2 deg, SSO		XCAM C3D2 (CMOS)	1200 x 1080 pixels Focal length: 45 cm	
3U	2018-12-03	University of North Carolina Wilmington	**SeaHawk**	580 km, 97.8 deg	120 m	push-broom design, with 4 linear array CCDs, each containing 3 rows of detectors	1800x 6000 pixels 8 bands deep	
6U	2017-08-14	NASA Jet Propulsion Laboratory	**ASTERIA**	400 km, 51.6 deg, ISS	30 m	Fairchild CIS2521 (CMOS)	2592 pixels x 2192 pixels Focal length: 85 mm Aperture diameter: 60.7 mm (f/1.4) Pixel size 6.5 µm x 6.5 µm Plate scale: 15.8 arcseconds per pixel Field of view: 11.2° x 9.6°	
6U	2018-02-02	GomSpace	**GOMX-4**	500 km	70 m	HyperScout camera from Cosine for hyperspectral images	4096 x 1850 pixels Spectral range: 400 - 1000 nm Spectral resolution: 15 nm Dynamic range: 12 bit SNR: 50-100	
6U	2019-09-05	ESA	**Phi-Sat-1**	450-550 km	VNIR 75 / TIR 390 (590km)	HyperScout-2, two spectral channels, each with 2D sensors operating in pushbroom mode.	FoV: VNIR 31 x 16 / TIR 31 x 16 Swath: VNIR 310 x 150 / TIR 310 x 150 Spectral bands: VNIR 45 / TIR 4 Spectral range [µm]VNIR 0.4 – 1.0 TIR 8.0 - 14	
6U	2022-12-31	KP Labs (FP Space)	**intuition-1**	?	?	hyperspectral instrument	Spectral resolution in the range of visible and near-infrared light The band is divided into 150 channels	

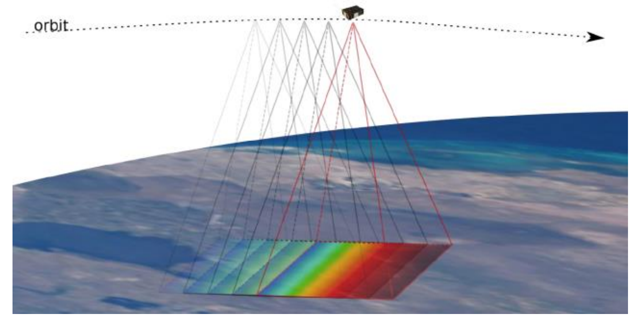
Example: GomX4, Technology Demonstrator

GOMX-4A camera (GomSpaceNanoCam):

Sjælland(DK)

Credit: GomSpace and Cosine; MarcoEsposito

GOMX-4B Hyperspectral Imager (Cosine Hyperscout I):



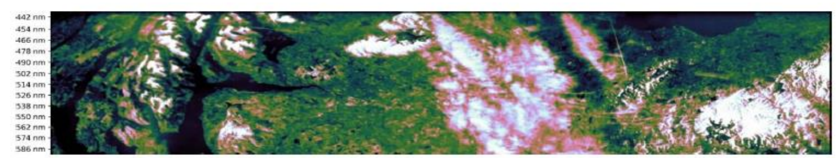


Figure 6: First light of HyperScout. False colour single image of the Scottish landscape between Glasgow and Edinburgh. Image acquired on the 20th of March 2018

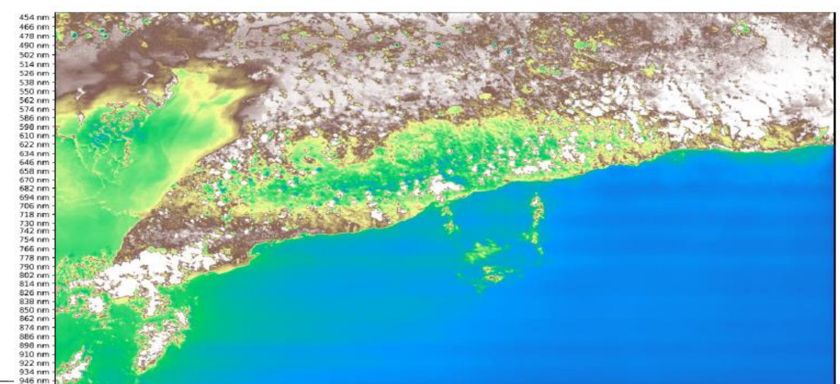
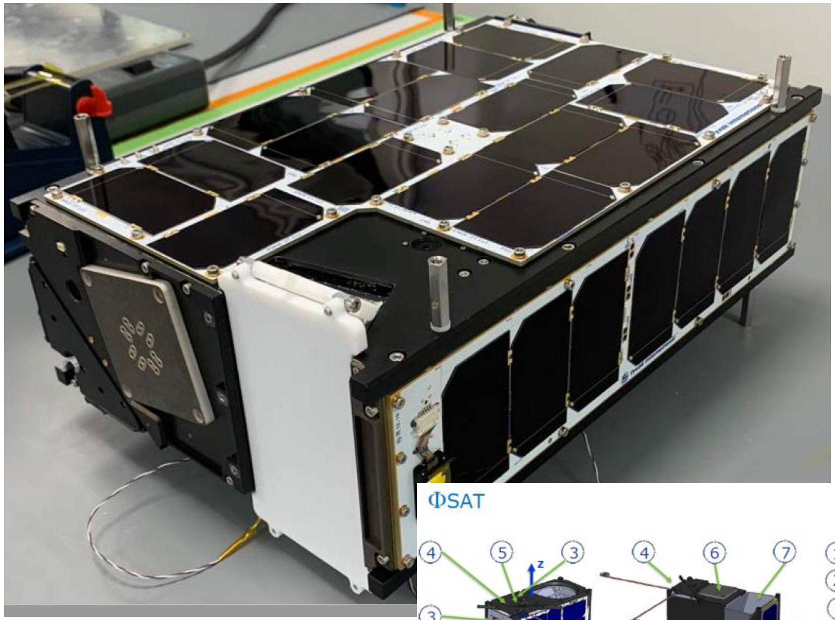
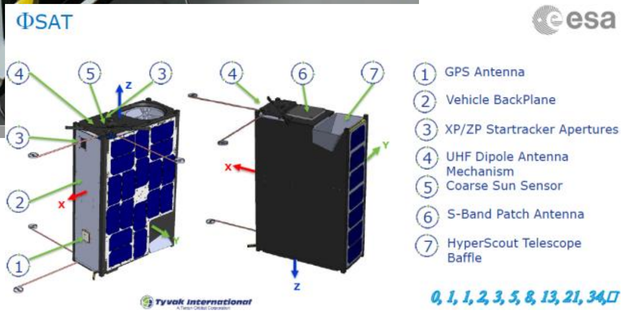


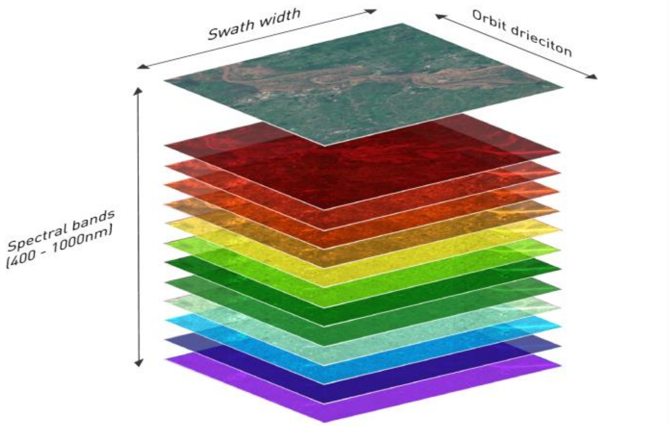
Figure 7: Commissioning image of HyperScout®. False colour single image of the southern Cuban coastline. Image acquired on the 26th of March 2018

Example: PhiSAT-1 On-board Processing

- FSSCat/PhiSat-1 technology demonstrator twin sat mission;
- Hyperspectral Sensor: Cosine Hyperscout II

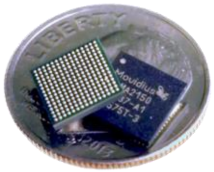


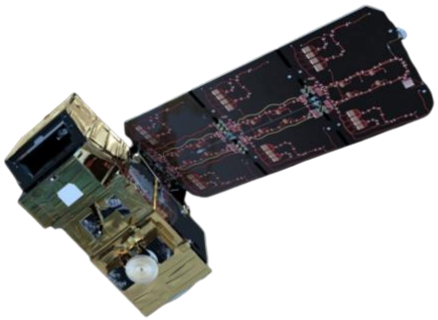


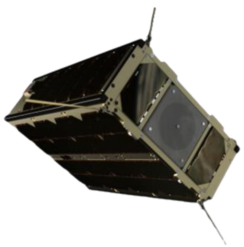


Example: PhiSAT-1

- Limited downlink capabilities
- AI processing on-board







560 Mbps

ESA Maspalomas, Spain

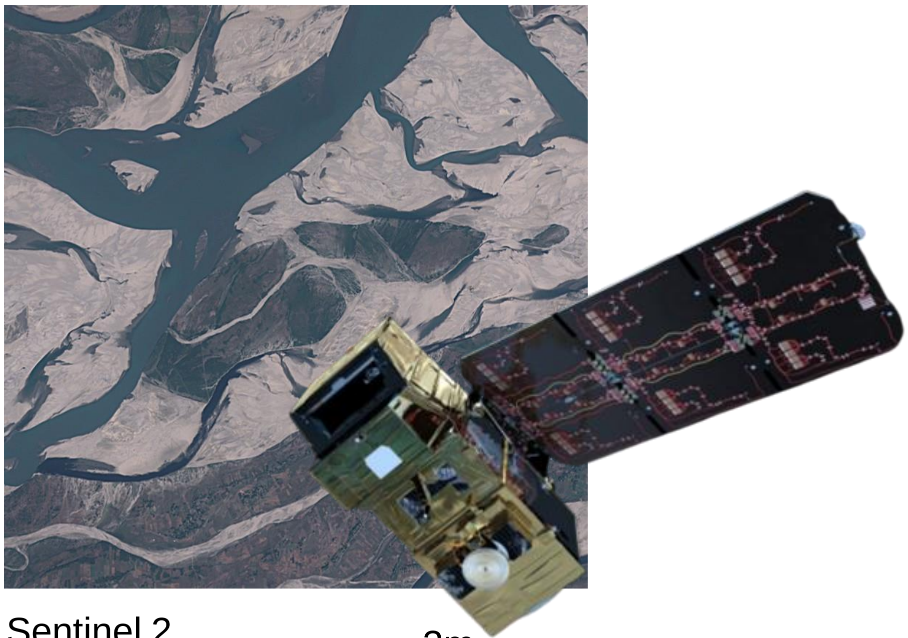
< 1Mbps

COTS ground station (ISIS)

Example: PhiSAT-1

Difference in Image Quality

- Geometric, spectral, radiometric resolution,
- S/N ratio, motion blur etc.



Sentinel 2
(10m resolution)

3m

HyperScout 2
(70m resolution, simulated)

0.3m

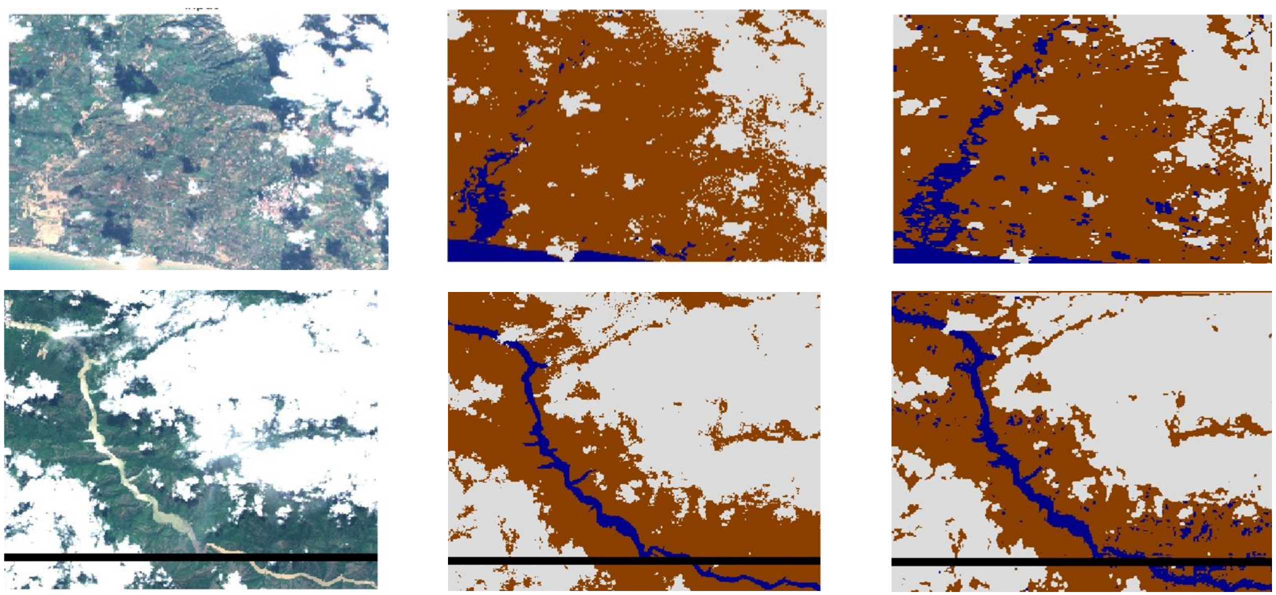
Antti Lipponen (Twitter @anttilip)

Example: PhiSAT-1: 'Flood and Cloud Detection in Orbit'

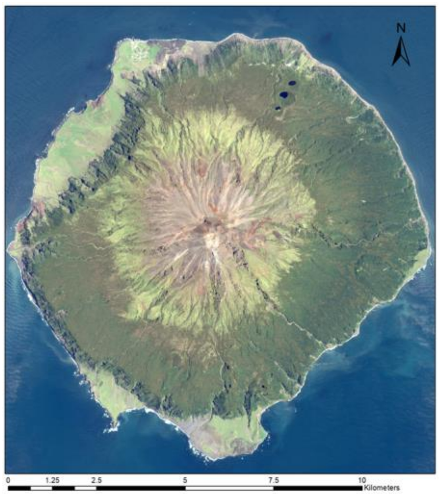
Development of a 'lean' deep learning algorithm to be deployed directly on the satellite

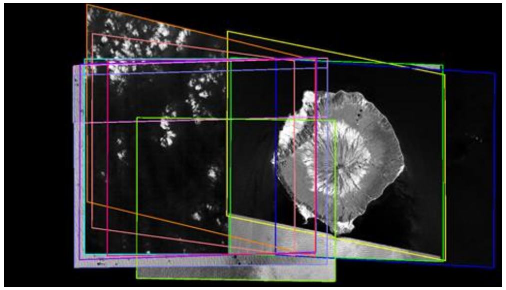
Results on Satellite Hardware:

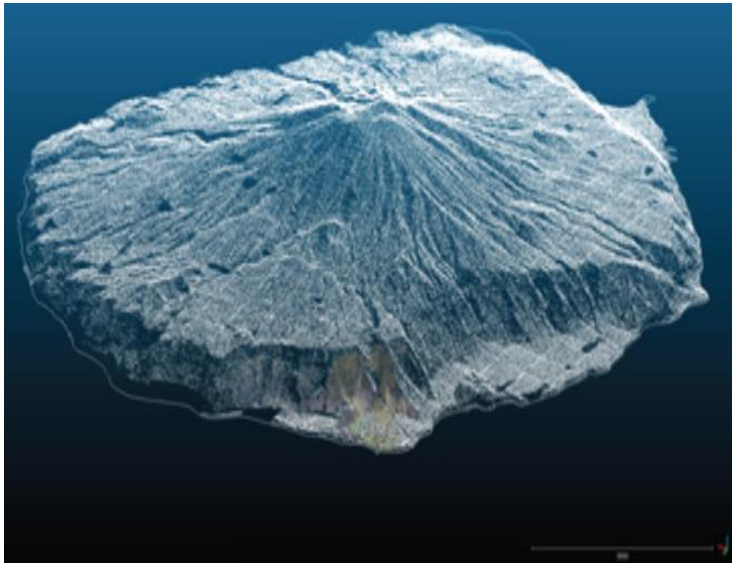
- Performance drop < 1%
- Deep learning NN: Model size < 0.5 MB
- 12MP image mapped in < 1 minute



Example Worldview 2: Trista da Cunha







- 3D topographic Mapping using WorldView2 archive data
- High resolution 3D DEMS and pointclouds where derived with 2m sample distance
- Geo positioning accuracy after spaceborne triangulation:

  RMSE of 0.48 pixels and a shift of 0.17 m in X, 0.05 m in Y and 0.04 m in Z

Conclusions and Outlook

- Image resolution quality of conventional EO Satellites will remain superior for the foreseeable future:
  - High and Very High resolution EO imaging
  - EO applications which require high accuracy requirements
- CubeSat technology will mature rapidly; technology demonstrators will soon become operational systems:
  - With low requirements on spatial resolutions and accuracy,
  - EO application which require high temporal resolution
  - Large constellations of ‘**small**’ EO satellites will provide higher temporal resolution and faster response or data acquisition times
- AI on small CubeSats satellites is expected to be a game changer
  - Onboard processing capabilities for a range of applications

Thanks for listening!

Many thanks to our teams at Uni.lu,

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RSS-Hydro, S.à r.l.-S

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