Sensor resolutions from space: the tension between temporal, spectral, spatial and swath

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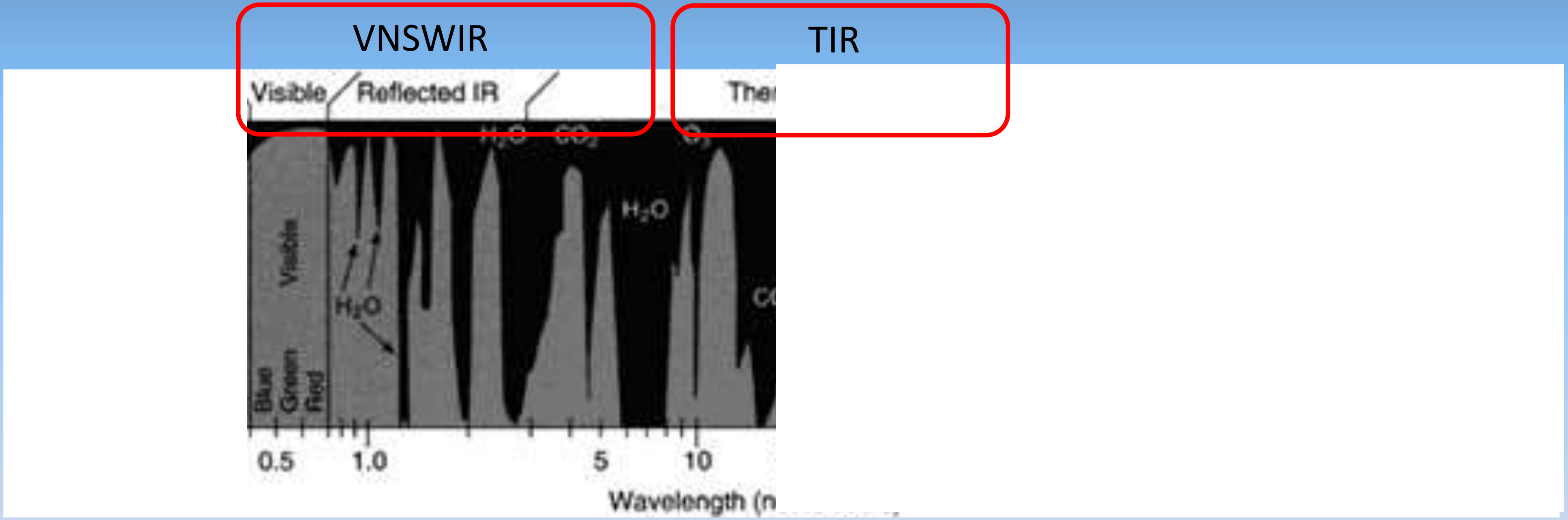
Presentation aims

1. Briefly summarize the different types of satellite image resolutions
2. Explain how satellite orbits affect resolution
3. Propose a method for establishing standard metrics for assessing satellite optical imaging sensor resolutions
4. Review the resolutions from current (plus near past & future) optical sensors in space
5. Propose a solution to the tension between spectral, spatial and temporal resolution

Passive Optical Sensors

Review of image resolutions is limited to **PASSIVE OPTICAL** multi-spectral sensors. That is - sensors that **receive** energy in the Visible (V), Near Infrared (NIR), Short wave (middle) Infrared (SWIR) and Thermal Infrared (TIR) parts of the EM Spectrum.



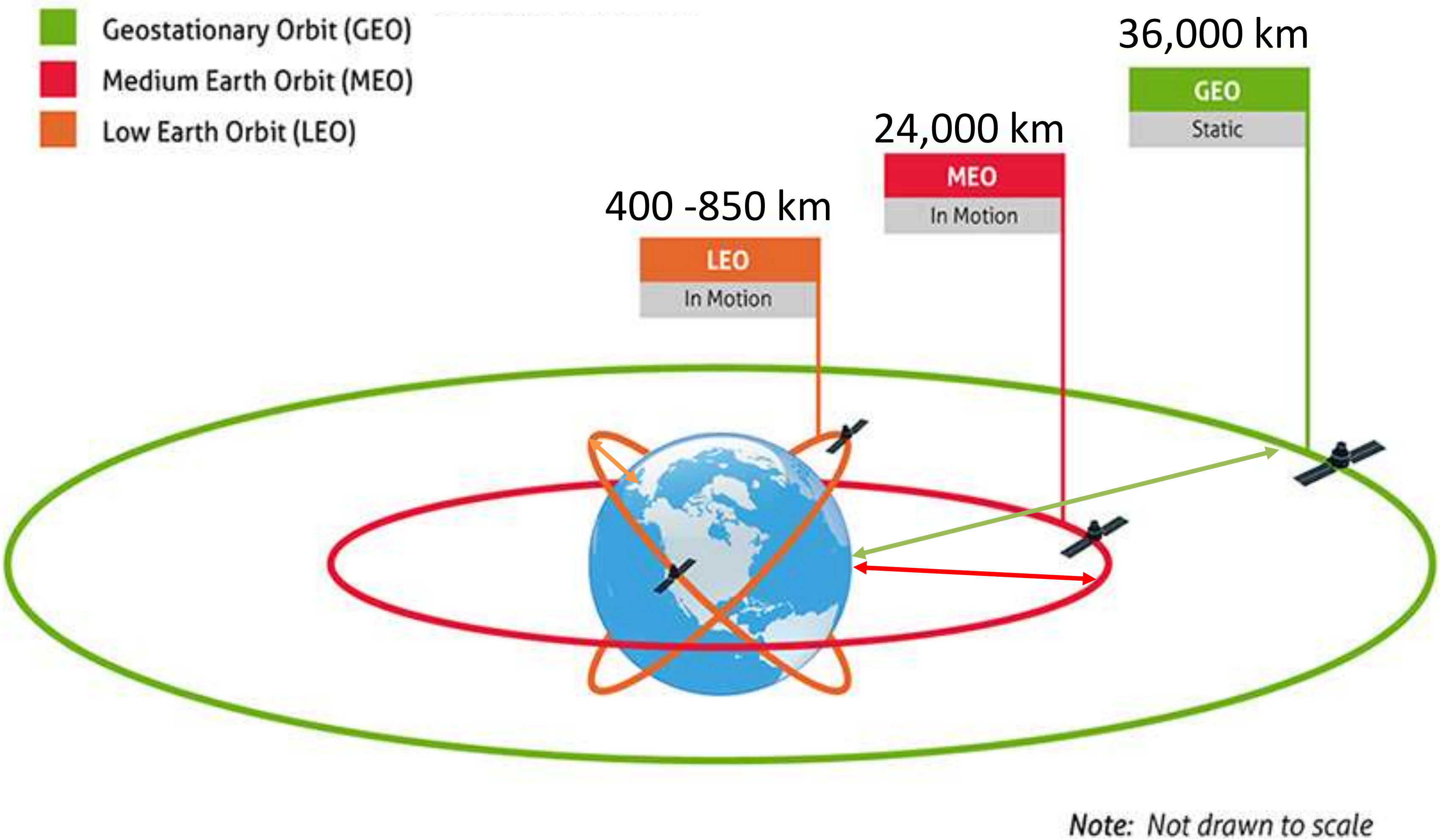
https://earthobservatory.nasa.gov/Features/RemoteSensing/remote_04.php

Image Resolution(s)

Five kinds of resolutions affect imagery and choice of imagery:

- SPATIAL
- SPECTRAL
- TEMPORAL
- RADIOMETRIC
- SWATH

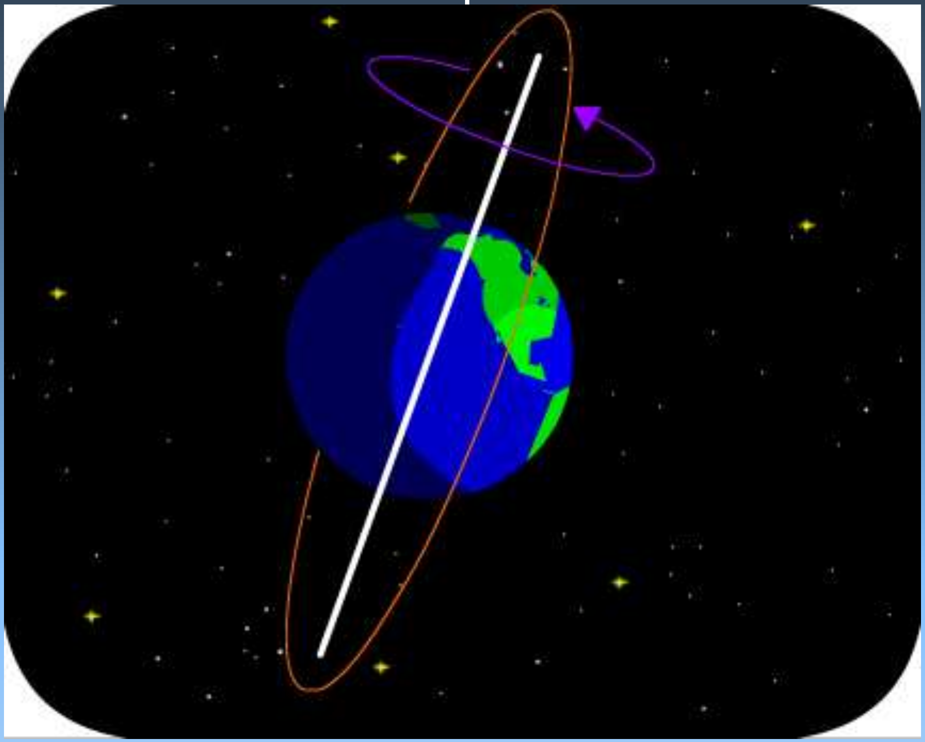
Image Resolutions Affected by Earth Satellite Orbits



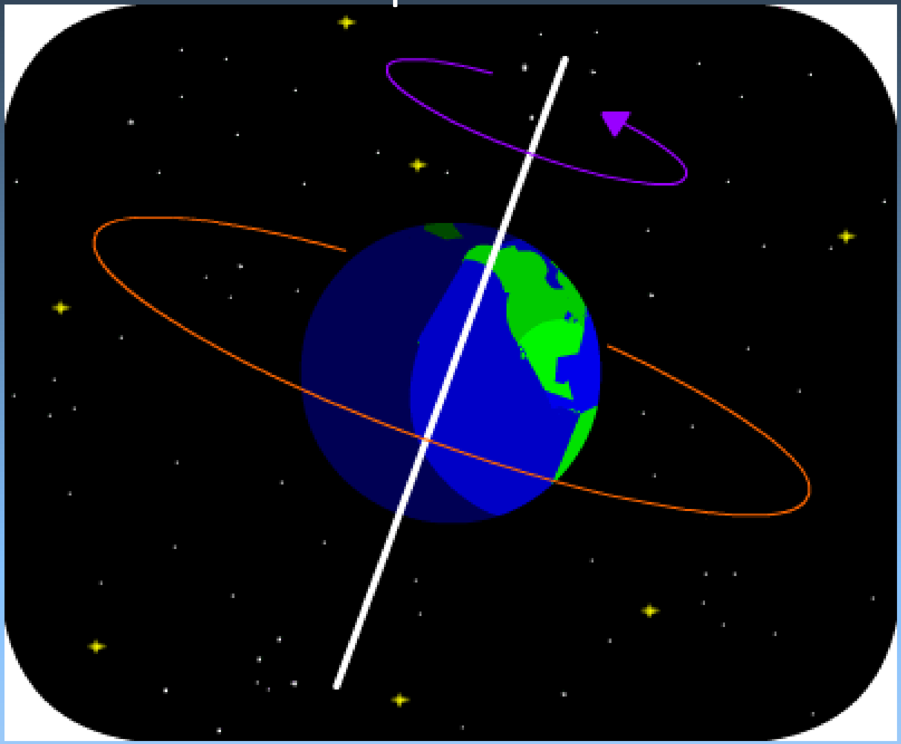
https://www.linkedin.com/pulse/how-do-geostationary-communication-satellites-get-stay-roger-hall

Imaging satellites – main orbits

Low Earth Orbit (LEO) – near polar



Geostationary Earth Orbit (GEO) - equatorial



http://www.s-cool.co.uk/gcse/physics/space/revise-it/the-solar-system

- High velocities wrt Earth
- Shorter dwell time per pixel
- Smaller image width (swath)
- Smaller pixels
- **Less frequent observations**

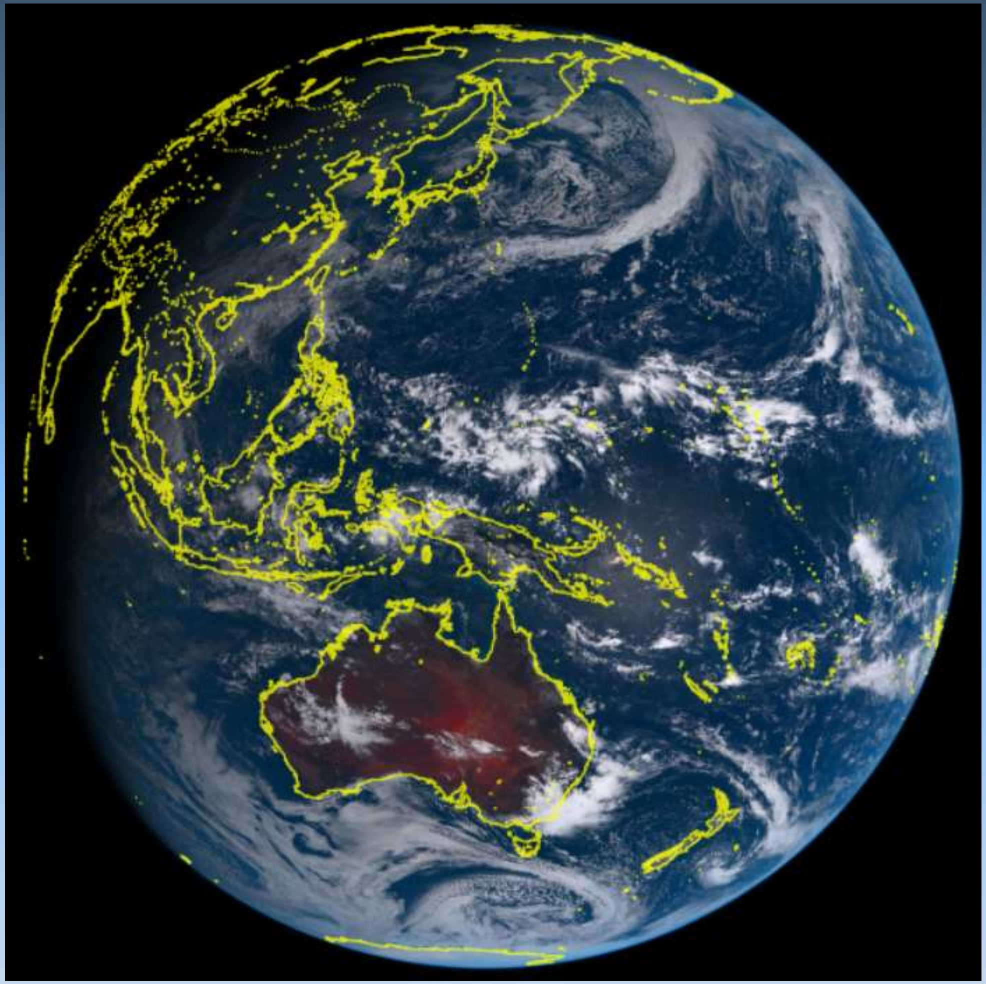
- Zero velocity wrt Earth
- Longer dwell time per pixel
- Larger image width (swath)
- Larger pixels
- **More frequent observations**

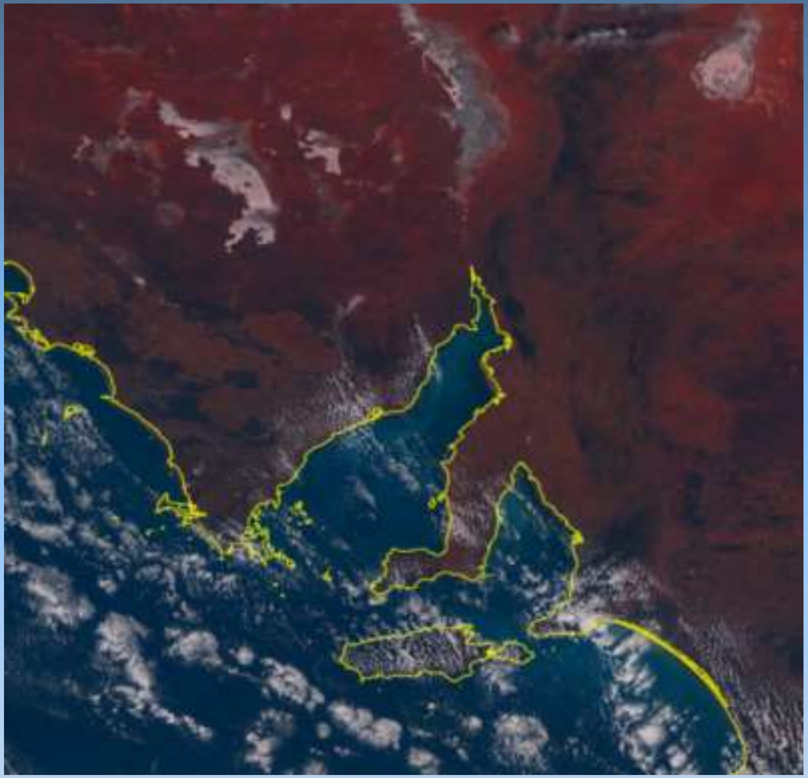
Spatial Resolution

- Spatial resolution is often equated to **pixel size**, or sometimes Ground Sampling Distance (**GSD**) ----- frequently < one pixel size.
- The **minimum distance** between two identical objects that the sensor can separately identify.
- The **higher** the **spatial resolution** the **smaller** the **pixels** (GSD) and the more detail that can be seen.
- Spatial resolution is also related to the contrast between an object and its background, the point spread function which is, in turn, a function of wavelength and keystone (spectral resolution).

Spatial Resolution: examples

Himawari AHI – 1000m pixels





http://himawari8.nict.go.jp/ 6 Nov 2017 10:20

Spatial Resolution: examples

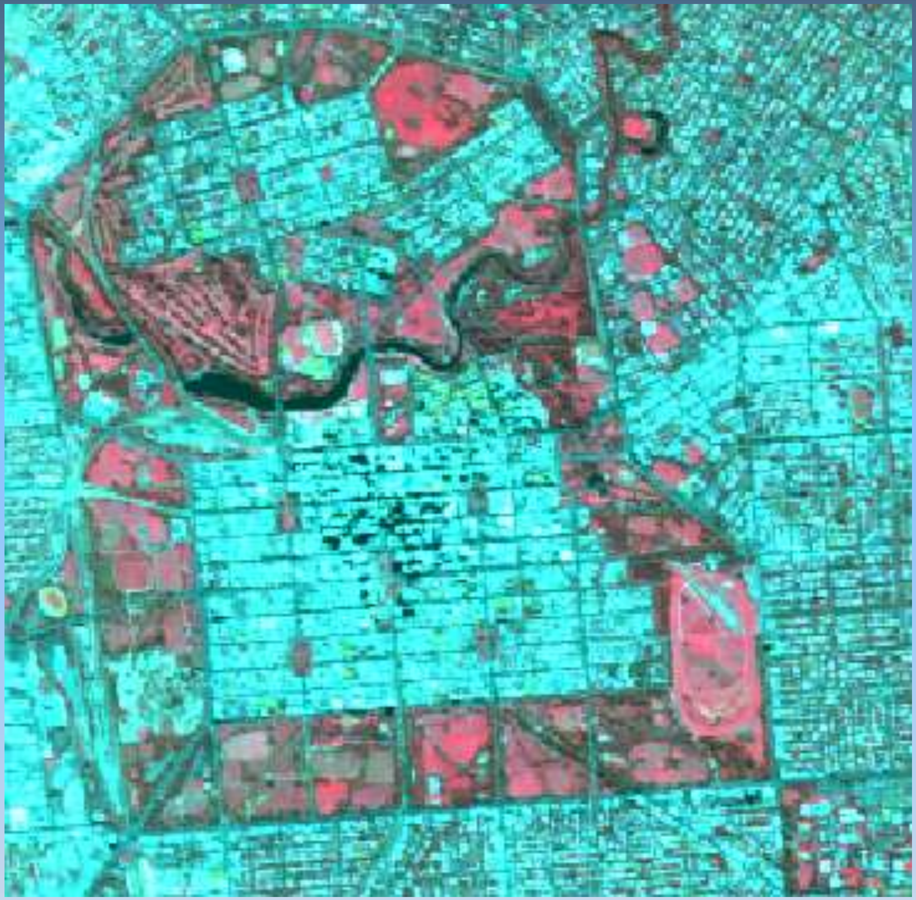
MODIS VNIR – 250m pixels

Adelaide City

Spatial Resolution: examples

10m pixels

VNIR ALOS 1



VNIR Sentinel 2

Spatial Resolution: examples

PlanetSource 31 March 2018 - 3m pixels

Pleiades Aug 2014 2m pixels

Spatial Resolution: examples

VNIR WV3 – 1.24m pixels

Mitcham , SA
shopping centre

Spatial Resolution

Spatial Resolution (SR) ~= 1 / Pixel Size (PS)

Generates a large dynamic range in values, so;

$$SR = 10 \, Log_{10} (1/PS)$$

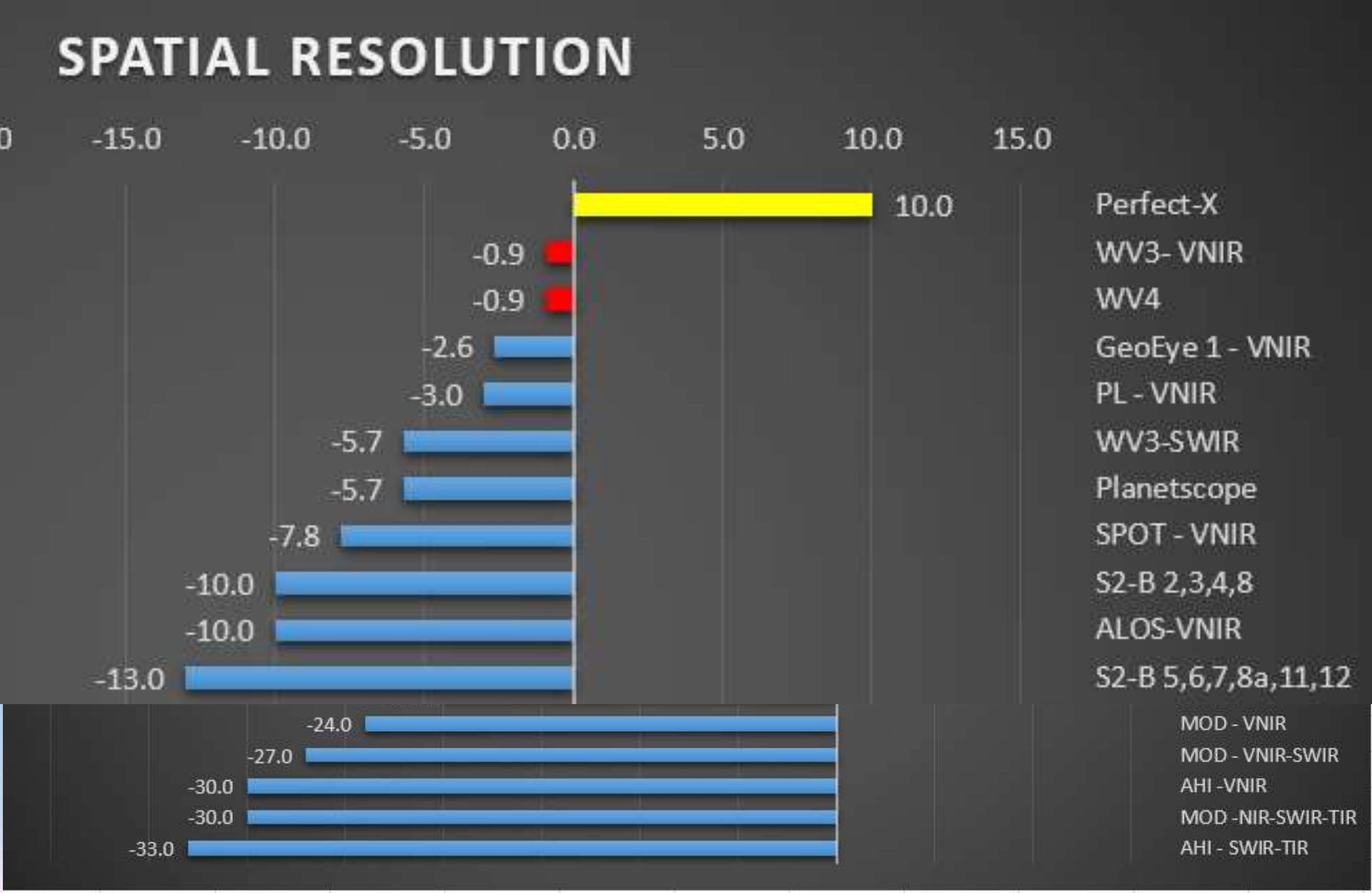
For a ***Sensor X*** on Satellite ***Perfect 1*** with PS = 0.1m

SR = 10

For a ***Sensor AHI – SWIR / TIR*** on Satellite *Himawari 9* with PS = 2000m

SR = -33.0

TOP TEN



SPATIAL RESOLUTION
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
10.0
Perfect-X
-0.9
WV3- VNIR
-0.9
WV4
-2.6
GeoEye 1 - VNIR
-3.0
PL - VNIR
-5.7
WV3-SWIR
-5.7
Planetscope
-7.8
SPOT - VNIR
-10.0
S2-B 2,3,4,8
-10.0
ALOS-VNIR
-13.0
S2-B 5,6,7,8a,11,12
-24.0
MOD - VNIR
-27.0
MOD - VNIR-SWIR
-30.0
AHI -VNIR
-30.0
MOD -NIR-SWIR-TIR
-33.0
AHI - SWIR-TIR

Spectral Resolution

- Spectral resolution describes the amount of spectral information that an image contains.

- Spectral resolution is related to the quality of EM dispersion system, sensitivity of detectors, wavelength, smile (spatial resolution), **no. of spectral samples (bands), narrowness of spectral samples**, **range of EM wavelengths** sampled and completeness of sampling across EM spectrum.

Spectral Resolution

Similarly to Spatial Resolution:

Spectral Resolution **SpR = 10 $\mathbf{Log_{10}}$ [10*N / ($\Delta\,\lambda$ * Avg $\delta\,\lambda$)]**

where N = no. of bands

Avg $\delta\,\lambda$ = average band width (nm) (FWHM)

$\Delta\,\lambda$ = spectral range of all bands (nm)

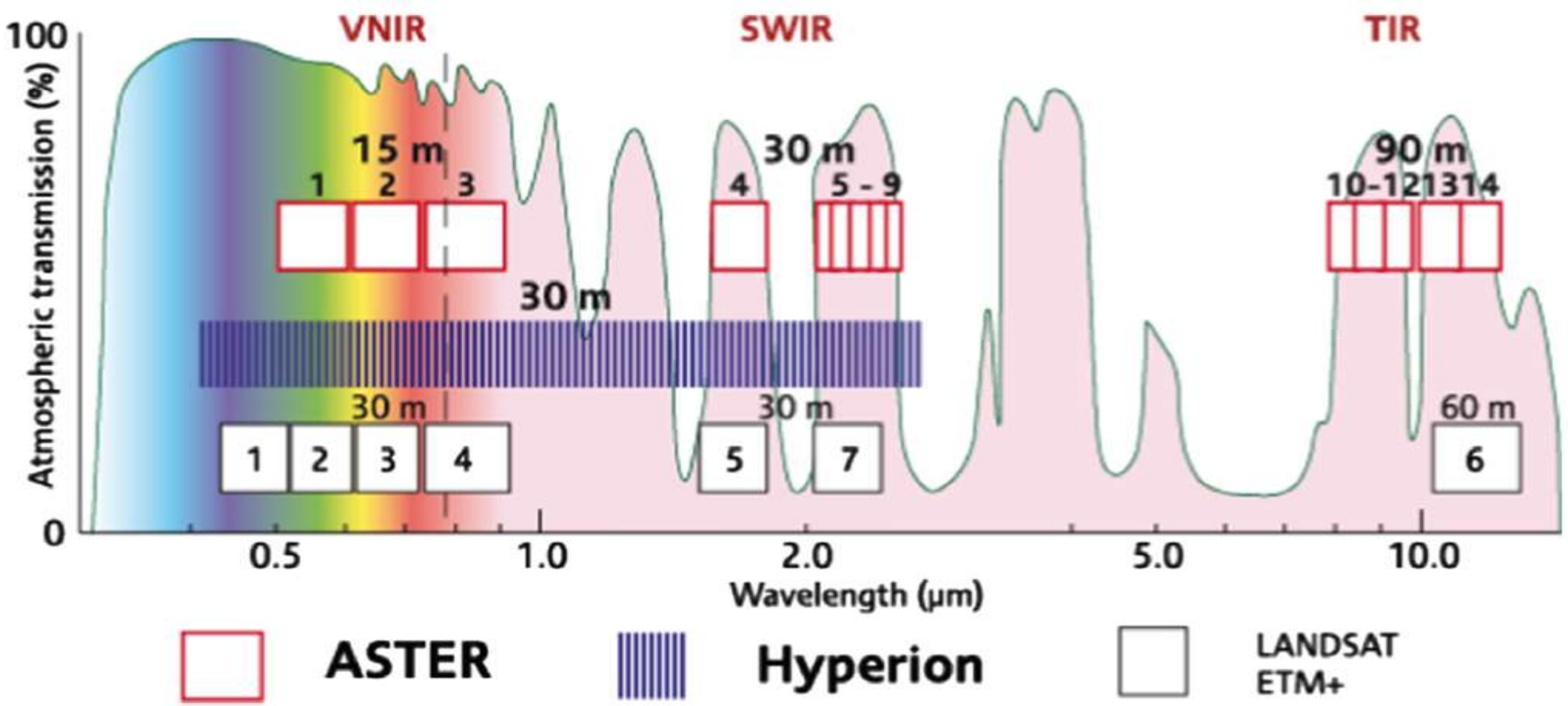
For a ***Sensor X*** on Satellite ***Perfect 1*** with N= 2500, Avg $\delta\,\lambda = 1$ nm and $\Delta\,\lambda$ = 2500 nm……………………. **SpR = 10**

For a *Sensor* ***EnMap*** *(*Environmental Mapping and Analysis Program - launching in 2019*)* with N = 244, $\Delta\,\lambda = 2030$ nm and Avg $\delta\,\lambda = 8.7$ nm ……………………………**SpR = -8.6**

For a *Sensor* ***TIR*** *(*Thermal Infrared*) on* ***Landsat 8*** with N = 2, $\Delta\,\lambda = 1910$nm and Avg $\delta\,\lambda = 800$ nm ……………………………**SpR = -48.8**

TOP SIX

Spectral sampling of Hyperion (244 b) vrs Landsat ETM+ (7 b) vrs ASTER (14 b)



Pour & Hashim, 2014 - SpringerPlus2014**3**:130 https://doi.org/10.1186/2193-1801-3-130

Temporal Resolution

- The temporal resolution of a sensor is the minimum time taken for that sensor to image the same section of the earth's surface.
- Most optical systems limited by cloud / weather.
- Usually given in days or hours, but recently in minutes.
- Dependent on **satellite orbit**, **ground resolution**, **spatial extent (swath width)** of image, digital on-board memory, data transmission rates and capability of sensor to change pointing angle.

Temporal Resolution

Similarly to previous resolutions:

Temporal Resolution **TR = 10 Log_{10} [1/ (RT]**

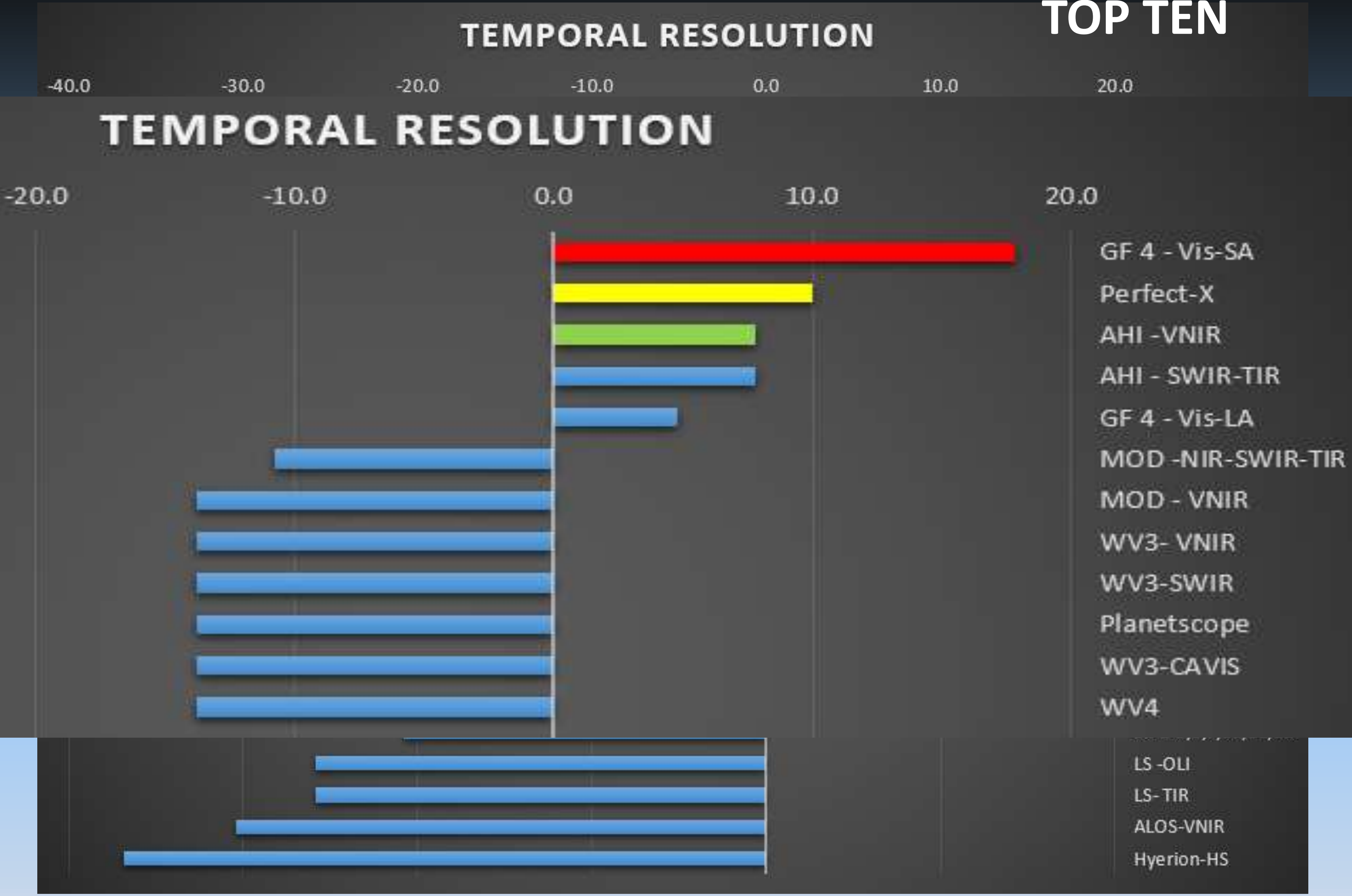
where RT = Revisit time (hrs)

For a ***Sensor X*** on Satellite ***Perfect 1*** with RT = 6mins (0.1 hrs) ………………**TR = 10**

For a *Sensor* ***GaoFen 4*** *(small area 400 x 400km) in* GEO with RT = 1 min …………………………………………….**TR = 17.8**

For a *Sensor* ***Hyperion*** *on* ***EO 1*** *(LEO)* with RT = 200 days ……………………………………………….**TR = -36.8**

TOP TEN


TEMPORAL RESOLUTION
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
TEMPORAL RESOLUTION
-20.0
-10.0
0.0
10.0
20.0
GF 4 - Vis-SA
Perfect-X
AHI -VNIR
AHI - SWIR-TIR
GF 4 - Vis-LA
MOD -NIR-SWIR-TIR
MOD - VNIR
WV3- VNIR
WV3-SWIR
Planetscope
WV3-CAVIS
WV4
LS -OLI
LS- TIR
ALOS-VNIR
Hyerion-HS

Radiometric Resolution

- Refers to the ability of the sensor to record differences in the magnitude of reflectance / emittance.
- Relates to the number of brightness levels that can be recorded for each pixel.
- Often termed quantization when referring to the number of levels that can be stored in the digital data.
- Quantization is based on powers of 2 (binary).
- Most modern satellite optical imaging sensors are either 10, 11 or 12 bit. …..thus **not a big differentiator of sensors**.

Swath Width Resolution

- Swath Width (SW) is the **width** of the **image** on the Earth's surface.
- SW is a function of satellite orbit and hence relative velocity, no. of detectors (pixels) across image, spatial resolution, on board digital memory, data transmission rates….
- SW Resolution (SWR) is based on a ideal SW (km) of 2,500 km

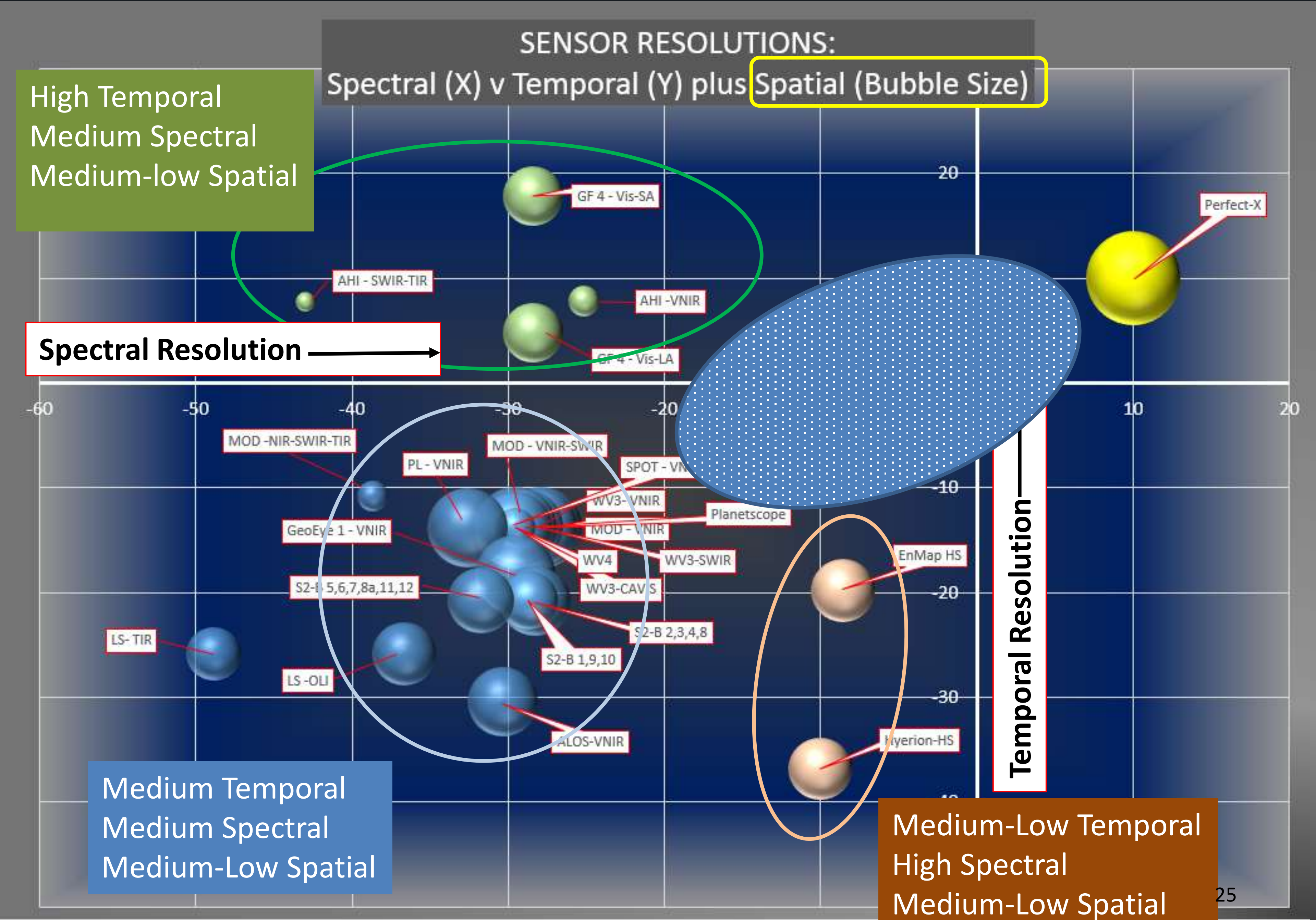
$$\mathbf{SWR = 10\ Log_{10}\ (10*SW/\ 2500)}$$

- For a ***Sensor X*** on Satellite ***Perfect 1*** with SW= 2500 km ……. **SWR = 10**
- For a *Sensor* ***AHI*** *on* ***Himawari 8/ 9*** with SW = 12,000 km ……………..**SWR = 16.8**
- For a *Sensor* ***Hyperion*** *on* ***EO 1*** with SW = 7.5 km…………. **SWR = -15.2**

Swath Width Resolution

ALL RESOLUTIONS
TOP TEN

or combine graphically …….



SENSOR RESOLUTIONS:
Spectral (X) v Temporal (Y) plus Spatial (Bubble Size)
High Temporal
Medium Spectral
Medium-low Spatial
Spectral Resolution
Temporal Resolution
GF 4 - Vis-SA
AHI - SWIR-TIR
AHI -VNIR
GF 4 - Vis-LA
Perfect-X
MOD -NIR-SWIR-TIR
PL - VNIR
MOD - VNIR-SWIR
SPOT - VN
WV3-VNIR
Planetscope
MOD - VNIR
GeoEye 1 - VNIR
WV4
WV3-SWIR
WV3-CAVIS
S2-B 5,6,7,8a,11,12
S2-B 2,3,4,8
S2-B 1,9,10
LS- TIR
LS -OLI
ALOS-VNIR
EnMap HS
Hyperion-HS
-60
-50
-40
-30
-20
10
20
-10
-20
-30
Medium Temporal
Medium Spectral
Medium-Low Spatial
Medium-Low Temporal
High Spectral
Medium-Low Spatial

The Resolution Gap

In some applications a gap exists when seeking combined resolutions:

- High spatial (0.5 – 2.5m; i.e. SR -4 to +3)
- High temporal (0.5 – 1 day; i.e. TR -14 to -10)
- High spectral (SpR -20 to 0)

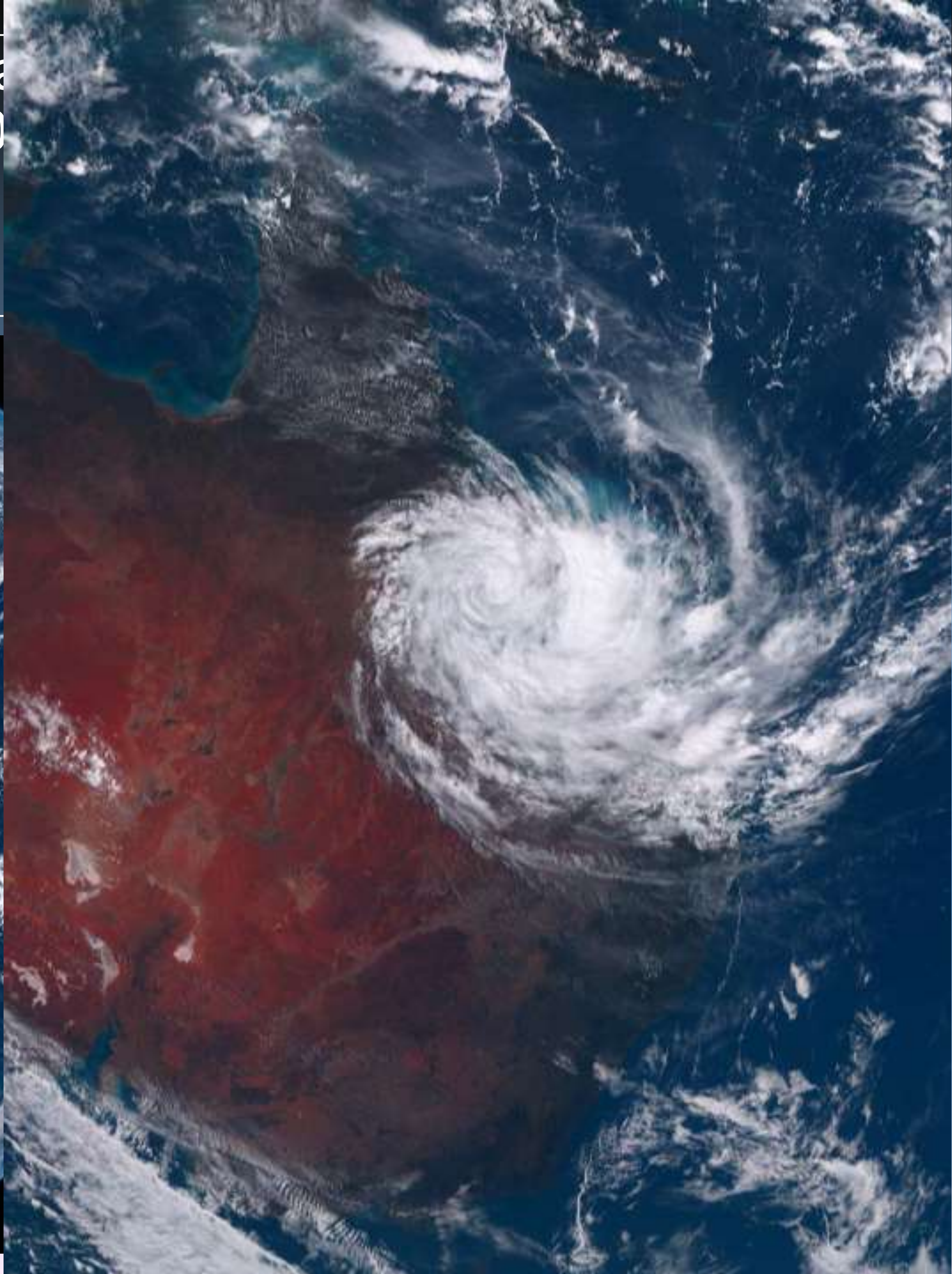
and at the same time have sufficient swath resolution (SWR) to cover application areas

Examples:

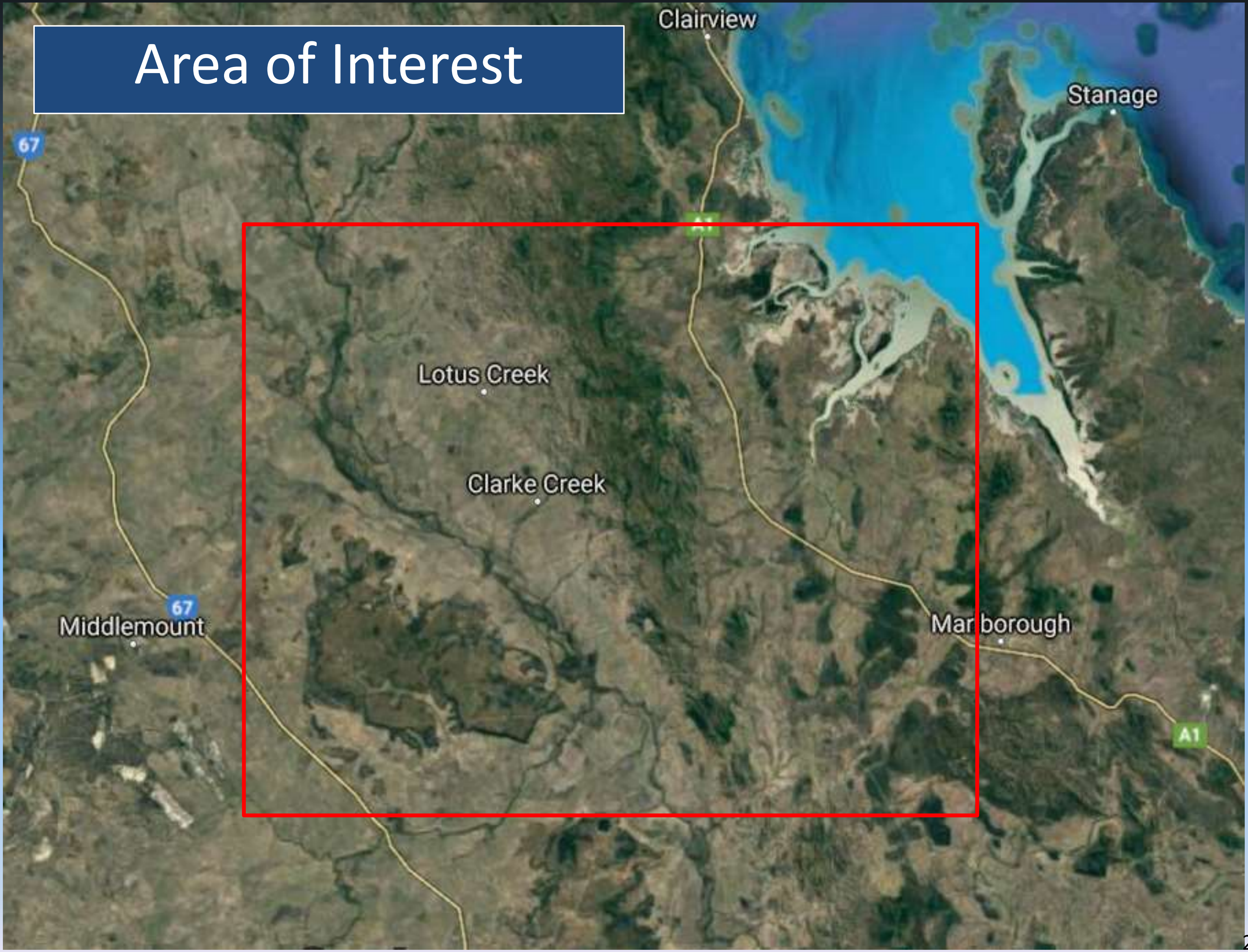
- Dynamic phenomena in disasters (fire, flood, earthquake …)
- Daily and weekly phenological changes in crops (grape vines, vegetables….)
- Detecting and mapping changes in algal booms in inland water systems

Cyclone Debbie from Hima
– JMA GEO satellite 140
35,793km

Late March 2017



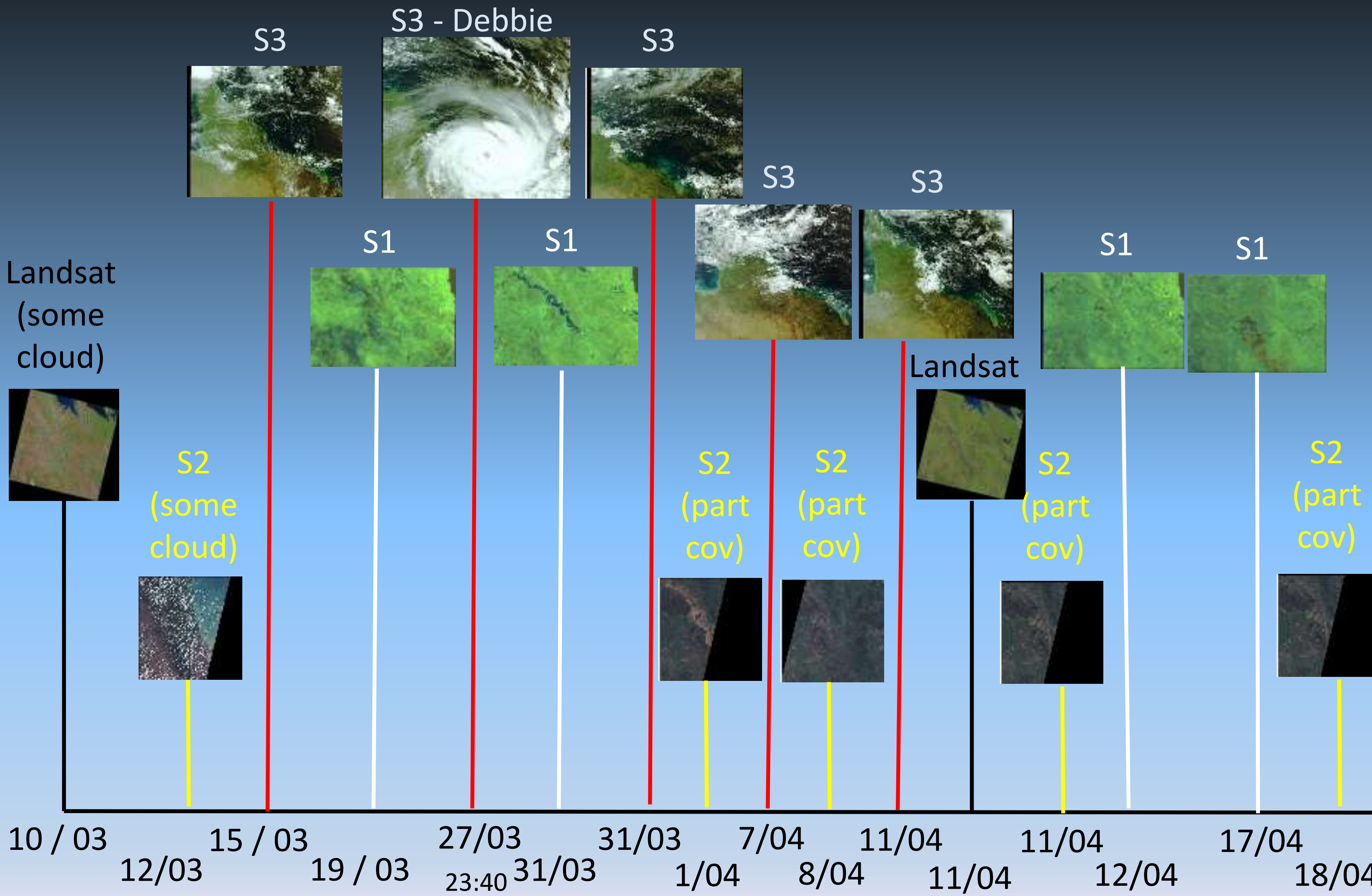
Area of Interest



Sentinel 2 - 1 & 11 April 17

SR ☑; SWR ☑; TR ☒; SpR ☒☑

EO Images re Cyclone Debbie – Timeline 4 EO stats



Potential Solutions

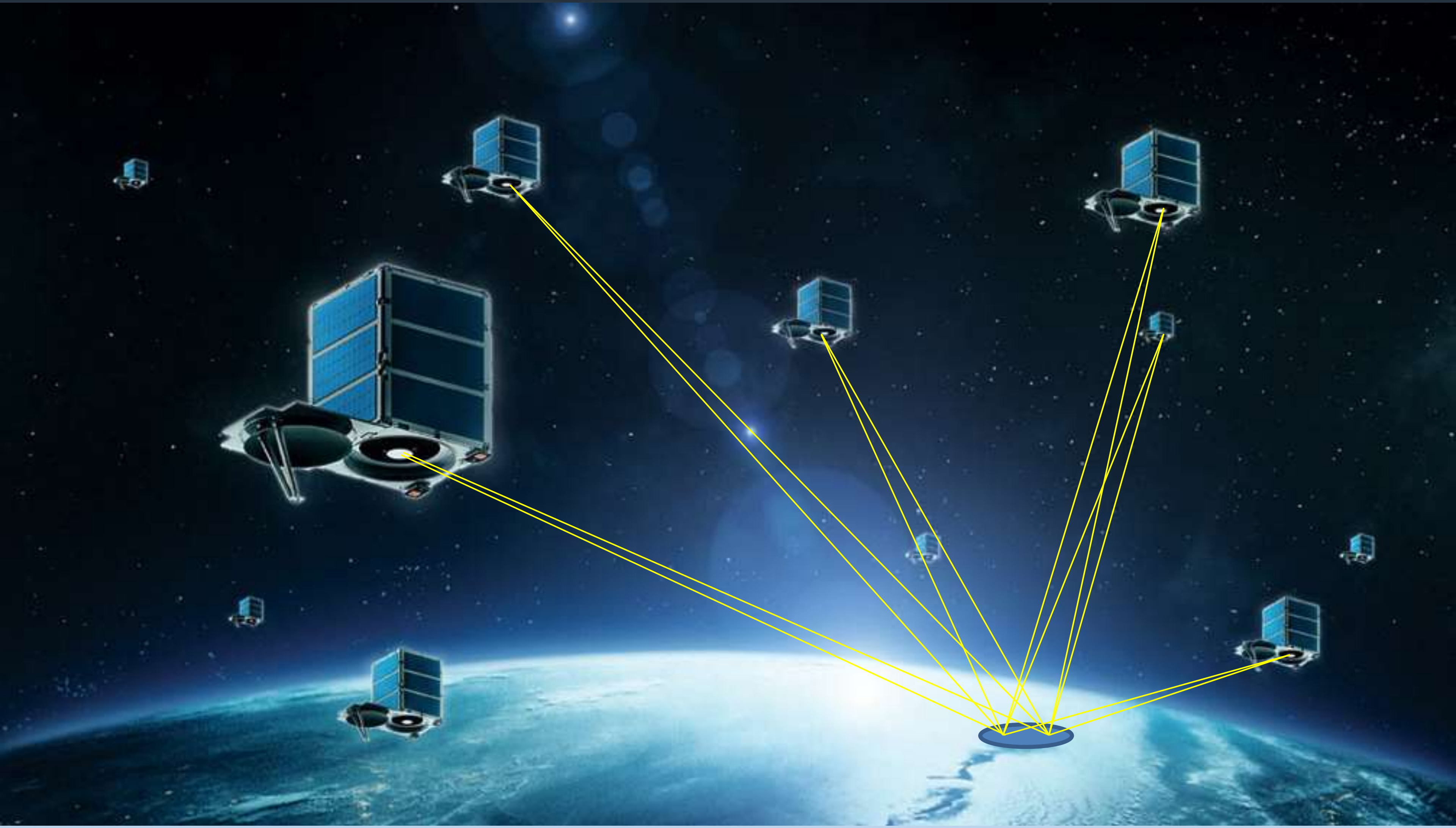
- A: Combine images with suitable resolutions from multiple satellite sensors – *issues due to non simultaneity of images, different viewing & illumination angles and use of different parts of EM spectrum*

- Two new solutions are:

  B. Improve the optical qualities of GEO sensors to provide higher Spatial and Spectral resolutions. GEO provides for extremely high Temporal resolution – *issues mainly due to focal length of optical system and very large mass of sensor.*

  C. Continue to expand on the use of constellations of small LEO and possibly MEO satellites, which simultaneously acquire imagery of the same location, thereby improving Spectral and Temporal image resolutions.

Solution C – the concept

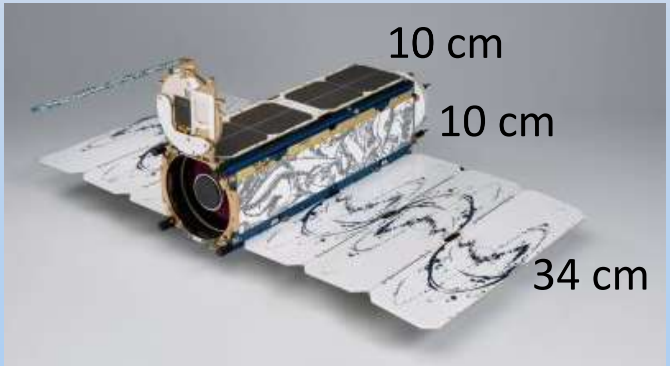


Modified from Keith 2015, http://eijournal.com/print/articles/earth-observation-embracing-the-new-space-environment-the-significance-of-eo-smallsat-constellations

Solution C – the concept

- Use of small sats – possibly cubeSAT, similar to those of Planet which uses 3U cubeSATS. Could also be a TubeSAT.

5kg mass; use of OTS hardware;
4 spectral bands; 3.7m pixels;
175 "sats"; temporal res. of 1 day



- Focal length needs to be double that of Planetsource leading to at least 6U - to provide ~1.5m pixel size.
- Spectral sampling needs to increase from 4 to 100 bands; with simultaneous observation by 10 stats flying in close constellation, providing 1000 spectral samples per pixel.
- On board data storage needs to increase by 50; use laser uplink to 3 master GEO (data collection, management and downlink (DCMD)) sats at 120 deg longitude separation.

Solution C – the concept & costs

- Require approx. 1500 cubeSATS (call them “crows”) to achieve global coverage each day. Less if 2D array frame sensors can be constructed with better characteristics than PlanetScope.
- LEO constellation at approx. 500km in sun-synchronous orbit for each “murder” of 10 “crows”.
- Mass of each “crow” likely to be 15kg leading to launch costs of $200K per crow when launched with other cubeSATS.
- Total launch costs of crow constellation approx. $300M
- Total construction cost of all crows at approx. $75M.
- Cost and launch of 3 GEO master DCMD sats approx. $300M
- Cost of ground stations and processing facilities at $150M

- **Grand Total of approx. $825M or say $1B**

ALL WE NEED IS YOUR CREDIT CARDS!

THANK YOU FOR LISTENING

References

Pour A. & Hashim M., (2014) ASTER, ALI and Hyperion sensors data for lithological mapping and ore minerals exploration, **SpringerPlus**, 4**3**:130, March 2014; https://doi.org/10.1186/2193-1801-3-130

*Keith (2015) Earth Observation embracing a new space environment: the significance of EO smallsat constellations, **Earth Imaging Journal** http://eijournal.com/print/articles/earth-observation-embracing-the-new-space-environment-the-significance-of-eo-smallsat-constellations*