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Polar Monitoring CCN: CRISTAL Orbit study

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List of Contents

1. Introduction

The CRISTAL orbit characteristics to fulfil user requirements was preliminary analysed in the second work package of the Polar Monitoring study (WP2), among the “observation system” of CRISTAL. However, given the complexity of the task, ESA decided to set up a Contract Change Notice (CCN) to specifically address this problematic.

The two main objectives of this CCN are to:

1) **Find another orbit candidate for the future CRISTAL mission.**
2) **Evaluate the current orbit candidates** suggested by ESA and CNES (see below), along with the potential new orbit candidate, to fulfil CRISTAL user requirements

The orbit new candidate research and the evaluation is based on the orbit candidates capability to fulfil clear specifications made by the MAG members before the study:

- **Weekly sampling** is first priority for sea ice thickness objective.
- **Monthly sampling** is first priority for land ice objective.
- For **Antarctica, monthly sub-cycle** will be sufficient; for **Greenland, <30 days sub-sampling** would be desirable.
- **Regular, homogeneous sampling** is generally favorable.
- Additional sub-cycles such as **4 days sub-cycle**, and **quarterly sub-cycles** are nice to have.
- **The orbit must complement Sentinel-3 orbit pattern.**
- **A 15 days sub-cycle for mid-latitude mesoscale** is desirable for oceanographic purposes and objectives but the lack of such sub-cycle **should not be a criterion** to reject an orbit.

2. Summary of the study

2.1. New orbit candidates research

To fulfil user requirements, the CRISTAL orbit must possess 3 main characteristics:

- northern and southern poles must be covered (+/- 88° at least) [MRD-040]
- a yearly cycle
- a sub-cycle < 10 days [MRD-050]

6 orbits have been already proposed by ESA and CNES before this study. Below is a table summarizing the orbit sub-cycles of these 6 candidates:

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1 747km	**2**	**7**	/	**30**	/	**365**	**67**
Case G2 820km	**5**	/	**14**	**33**	/	**372**	**113**
Case 3 805km	**4**	/	/	**35**	/	**365**	**66**
Case 5 609km	/	**7**	/	**29**	/	**363**	**167**
ICESat-2 493km	**4**	/	/	**29**	**91**	/	/

Figure 1: List of sub-cycles for the orbit candidates proposed by ESA & CNES. Indicated altitude is a mean value from the CLS orbit simulator.

Orbit sub-cycle definition is highly important, as they indicate the repetition of an homogeneous sampling on-ground. As it can be noticed in the table above, geodetic orbits can have several sub-cycles. Nevertheless, none of the current proposed orbit alone satisfy all the MAG requests listed before.

As a first task of this CCN (WP2), intensive researches were made at CLS to assess if such an orbit could exist. Unfortunately, it is not the case, and a trade-off will have to be made. In particular, it is not possible to have a 4-days and a 7-days sub-cycle at the same time, given the others constraints (latitude coverage, yearly cycle). It is also challenging to find an orbit with both bi-weekly and monthly sub-cycles. Lastly, quarterly sub-cycles are also not easy to match with the other requirements.

Initially it was planned to add one single orbit to the exiting candidates. But 3 new interesting candidates were found at CLS, with different characteristics. As it was not possible to make a clear choice between them, given their different assets, these 3 orbits candidates were kept for the following of the study. The table below presents the orbit sub-cycles for these 3 candidates:

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
CLS1 *751km*	**2**	**7**	**19**	**31**	/	**367**	**112**
CLS2 820km	**5**	/	**19**	**33**	**85**	**373**	/
CLS3 *794km*	**3**	**7**	/	**31**	**86**	**368**	/

Figure 2: List of sub-cycles for the orbit candidates proposed by CLS. Indicated altitude is a mean value from the CLS orbit simulator.

2.2. Orbit candidates evaluation

2.2.1. Diagnoses definition

To evaluate the orbits side by side, different diagnoses were performed over the three surfaces (WP1):

- Ice charting sampling & weekly products capability **for sea-ice**
- Ability to sample dynamic regions of the ice sheets at 30-day frequency **for ice sheets** (for monthly products capability). And in quarterly period additionally.
- Decorrelation of mesoscale signals in space/time and polar ocean analysis **for ocean**. With a polar ocean strategy originating from G.Dibarboure (CNES)

2.2.2. Analyses summary

- **Sea-Ice**

Ice charting

To quantify the goodness of orbit candidates for ice charting, we calculated the ratio of polygons that were flown over to the total number of polygons. This hit rate was calculated for all orbits for all 52 weekly ice charts. Time series of hit rates, as well as average hit rates throughout the year can be found in appendix 2 (slide 15)

The differences between orbit candidates are small. Average hit rates are between 70% and 76%. Hit rates for CRISTAL orbit candidates are higher during summer, when all of the ice lies high North where the CRISTAL ground tracks are dense. Sentinel-3 with its lower inclination orbit however misses most of the summer ice. During winter when there is ice further south, it is more likely for an ice polygon to fall between CRISTAL ground tracks. Orbit Case 3 seems marginally less suited for sea ice mapping. However, the difference between the best and the worst (case 5 and case 3 respectively) is only 5%.

To study how different candidate orbits complement the Sentinel-3 measurements, we also calculated how many polygons were hit by either CRISTAL orbit candidate or the Sentinel-3A and B orbits. The time series of hit rates over one year is shown in appendix 2 (slide 17). Now the differences between CRISTAL orbit candidates become negligible, and all of the cases catch on average between 90% and 91% of the polygons. However, it should be noted that Sentinel-3AB measurements are expected to benefit from the snow on sea ice estimates CRISTAL will provide.

Thus even when CRISTAL will complement the Sentinel-3 mission, an orbit pattern covering maximum number of ice polygons is preferable.

Weekly sampling

When looking at CRISTAL alone, 7 day repeat is better for weekly ice charting than a 4 or 5 day one. However, the difference is small: On average 78% vs 72% of polygons caught.

However, if we assume that Sentinel-3 satellites will provide dense measurements for areas south of 82 N, difference between CRISTAL orbit candidates becomes negligible: ~ 90% of the polygons are caught regardless of CRISTAL orbit.

• Ice-sheet

The assessment of the candidate orbits over land ice consisted of analysis over Greenland and Antarctica. In line with MRD-350, we focused our evaluation on the sampling of 'outlet glaciers and boundaries of Greenland and Antarctica', where major changes occur and therefore monthly to seasonal sampling is required. Specifically, we evaluated (1) the proportion of these regions sampled, on average, over monthly, quarterly and annual epochs, and (2) the consistency of this sampling over multiple monthly and quarterly epochs. The domain was defined as follows:

1. Antarctica: outlet glaciers where the surface velocity exceeded 100 m/yr.
2. Greenland: the union of the ablation zone and regions in a state of dynamical imbalance.

The assessment was undertaken considering the CRISTAL orbit in isolation, and the CRISTAL orbit in combination with the Sentinel-3A/B nominal acquisition scenario.

In the case where each CRISTAL orbit was assessed in combination with Sentinel-3A/B, there was no standout 'optimal' candidate; all CRISTAL candidate orbit configurations performed very well. When the candidate CRISTAL orbits were considered in isolation, there was greater differentiation, with 5 options offering 'optimal' coverage. These were ICESat-2, Orbit 5, CLS-1, CLS-2 and CLS-3. Between these 5 'optimal' scenarios, there were small variations, and so the decision of which to favour depends upon the prioritisation of the epoch sampling length; essentially whether the priority is to optimise monthly, quarterly or annual sampling coverage:

- ➢ If total coverage over an annual cycle is deemed to be not important, then the ICESat-2 orbit is marginally better, offering a ~2-3% improvement in coverage over monthly and quarterly time periods, as compared to the other 4 scenarios.

- ➢ If annual coverage is important, then one of the other 4 orbits should be chosen, because they provide ~ 5% (Antarctica) and 13% (Greenland) better coverage than the ICESat-2 orbit over an annual cycle. Between these 4 orbits:
  - o If annual + monthly sampling is to be optimised, then Orbit 5 is the best choice.
  - o If annual + quarterly sampling is to be optimised, then CLS1, CLS2 and CLS-3 should be favoured; with all 3 provide broadly equivalent sampling statistics.

- **Ocean**

Oceanic mesoscale

To evaluate the orbits with regards to their capabilities to sample mesoscale signals, we adopted the approach from Dibarboure et al. [2018]. The objective is to represent the space and time distribution of the orbit tracks, to analyse the orbit capacity to decorrelate oceanic mesoscale signals. More details, illustrations and results can be found in appendix 2 (slides 41 – 43)

The analysis shows 3 orbit candidates can efficiently sample oceanic mesoscale signals: Case G2, CLS1 and CLS2. While the other candidates are not adapted. This is notably explained by the lack of a bi-weekly sub-cycle for these candidates.

Polar mesoscale

Oceanic eddies spatial scales are much smaller at high latitude compare to mid-latitude. Typical eddy radius is 5 - 15km over polar ocean [Timmermans et al., 2008 ; Nurser & Bason, 2014]. Subsequently only a yearly (sub)-cycle is capable to reach these spatial scales (5-15km). The orbit strategy for polar ocean must therefore be considered as CRISTAL part of a global constellation.

G.Dibarboure already transmitted a detailed approach to find the optimal orbit for polar oceanic mesoscale. The objective is to determine the sub-cycles suiting different applications:

- **First sub-cycle : 2 to 4 days:** To collect independent (decorrelated) L3 measurements every 1 to 5 days for CMEMS model assimilation ; and to assemble low spatial resolution L4 maps for rapid signals
- **Second sub-cycle : ~15 days:** To collect denser homogeneous (albeit insufficient) sampling for slower eddies in bimonthly to monthly maps
- **Third sub-cycle : ~30 days:** Same purpose as before
- **Other sub-cycles (60 days or more)** can be added

Based on the candidate's sub-cycles (Figure 1), we considered three orbits as "sub-optimal" to reach these specifications: G2, CLS1 & CLS2. In particular because these orbits have a bi-weekly sub-cycle.

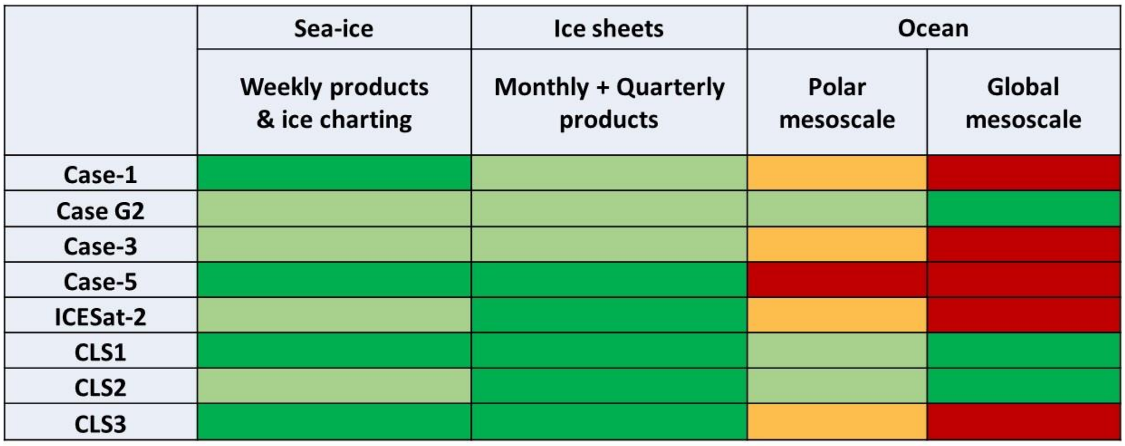
Four candidates are considered average: Case-1 ; CLS2 ; Case-3 ; ICESat-2. Because these orbits lack a bi-weekly sub-cycle.

One candidate is considered not adapted: Case-5. Because it has neither a bi-weekly sub-cycle and a 2-4 days sub-cycle.

Finally, we also consider that this polar mesoscale strategy, with CRISTAL part of an altimetry constellation, must be refined and matured. This was out of scope for this study.

2.2.3. Results summary

The orbit candidates were ranked in the table below as optimal (dark green), sub-optimal (light green) ; average (yellow) and not adapted (red).



	Sea-ice	Ice sheets	Ocean	
	Weekly products & ice charting	Monthly + Quarterly products	Polar mesoscale	Global mesoscale
Case-1	🟩	▨	🟨	🟥
Case G2	▨	▨	▨	🟩
Case-3	▨	▨	🟨	🟥
Case-5	🟩	🟩	🟥	🟥
ICESat-2	▨	🟩	🟨	🟥
CLS1	🟩	🟩	▨	🟩
CLS2	▨	🟩	▨	🟩
CLS3	🟩	🟩	🟨	🟥

Figure 3: Orbit evaluation summary table

The complementarity with Sentinel-3 was also analysed. When Sentinel-3 is added in the orbit analyses, all orbit candidates are optimal for ice sheet & sea ice surfaces and thus fulfil the user requirements.

All orbit candidates are well designed to address mission requirements over ice surfaces.

- <u>For sea-ice</u>, best candidates are **Case-1 ; Case-5 ; CLS1 & CLS3**, thanks to the 7 days sub-cycle
- <u>For ice-sheets</u>, best candidates are:
  - **ICESat-2** if total coverage over an annual cycle is deemed to be <u>not important</u>
  - **Case-5, CLS1, CLS2, CLS3** if annual coverage <u>is important</u>. Case-5 providing the best performances for monthly sampling. CLS1, CLS2, CLS3 very close with a better quarterly sampling
- <u>For ocean,</u> best candidates are **Case G2 ; CLS1 & CLS2** as they provide the most efficient sampling of oceanic mesoscale signals, and are adapted for a polar mesoscale multi-mission strategy. Case-5 is the worst.

Overall, the orbit CLS1 seems to perform best from all the orbit candidates when the requirements for oceanography (polar mesoscale and global mesoscale) is taken into account.

References

Dibarboure, G.; Lamy, A.; Pujol, M.-I.; Jettou, G. The Drifting Phase of SARAL: Securing Stable Ocean Mesoscale Sampling with an Unmaintained Decaying Altitude. *Remote Sens.* **2018**, *10*, 1051.

Nurser, A. J. G. and Bacon, S.: The Rossby radius in the Arctic Ocean, Ocean Sci., 10, 967–975, https://doi.org/10.5194/os-10-967-2014, 2014.

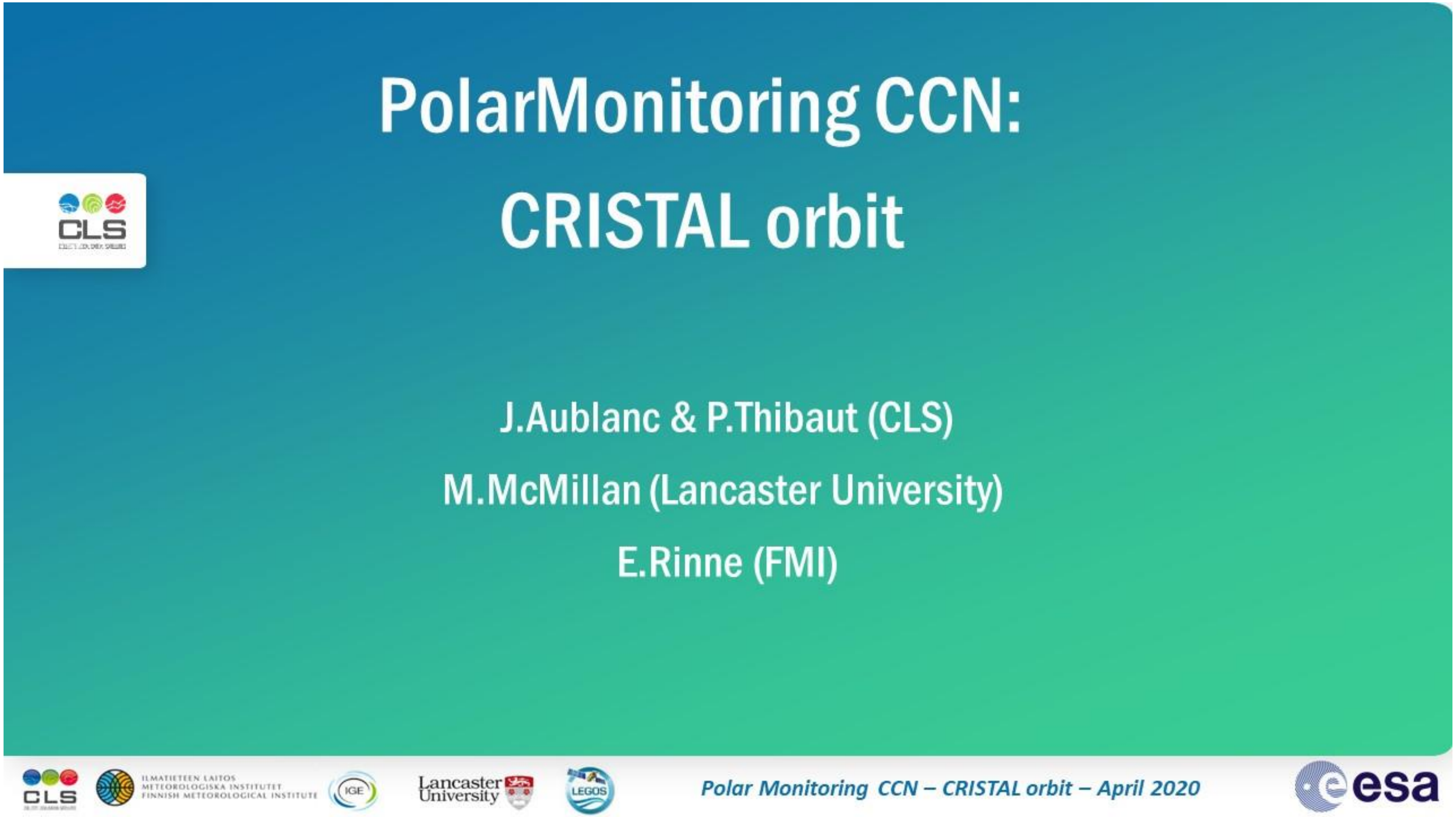
Timmermans, M., J. Toole, A. Proshutinsky, R. Krishfield, and A. Plueddemann, 2008: Eddies in the Canada Basin, Arctic Ocean, Observed from Ice-Tethered Profilers. *J. Phys. Oceanogr.*, **38**, 133–145, https://doi.org/10.1175/2007JPO3782.1.

Appendix 1: orbits technical parameters

The following table shows the parameters used to generate the orbit candidates with the CLS orbit simulator. Please note that the eccentricity chosen remains arbitrary, and does not have any impact on the cycle / sub-cycles durations. Please note also that it was out of scope to assess all the Kepler parameters in details in the frame of this study.

	Input					Output		Orbit additional information	
	Inclination	**eccentricity**	**N revolutions per day**	**P fraction**	**Q cycle duration (days)**	**mean altitude (km)**	**orbit semi-major axis (km)**	**exact nb of revolutions per day**	**nb of revolution per cycle**
Case-1	**92°**	**0.001**	**14**	**158**	**365**	**747**	**7109.780**	**14.43287**	**5268**
Case G2	**92°**	**0.001**	**14**	**79**	**372**	**820**	**7183.147**	**14.2123**	**5287**
Case-3	**92°**	**0.001**	**14**	**94**	**365**	**805**	**7167.964**	**14.25753**	**5204**
Case-5	**92°**	**0.001**	**14**	**313**	**363**	**609**	**6972.150**	**14.8623**	**5395**
ICESat-2	**92°**	**0.001**	**15**	**22**	**91**	**493**	**6855.917**	**15.2418**	**1387**
CLS1	**92°**	**0.001**	**14**	**154**	**367**	**751**	**7114.138**	**14.4196**	**5292**
CLS2	**92°**	**0.001**	**14**	**79**	**373**	**820**	**7183.339**	**14.2118**	**5301**
CLS3	**92°**	**0.001**	**14**	**107**	**368**	**794**	**7156.847**	**14.2908**	**5259**

Appendix 2: Slides presented to the MAG members, showing all the analyses & results



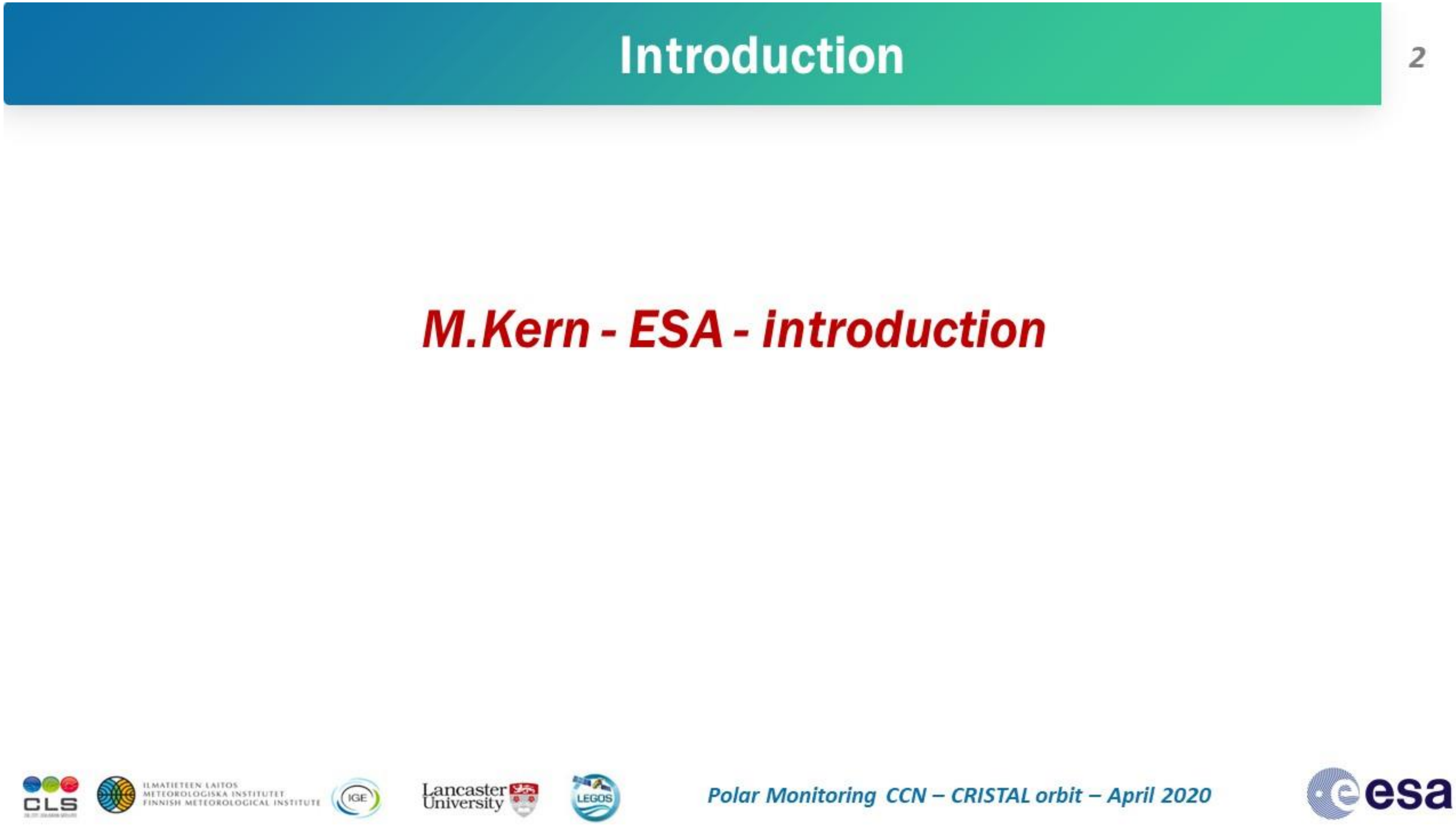
PolarMonitoring CCN: CRISTAL orbit

J.Aublanc & P.Thibaut (CLS)

M.McMillan (Lancaster University)

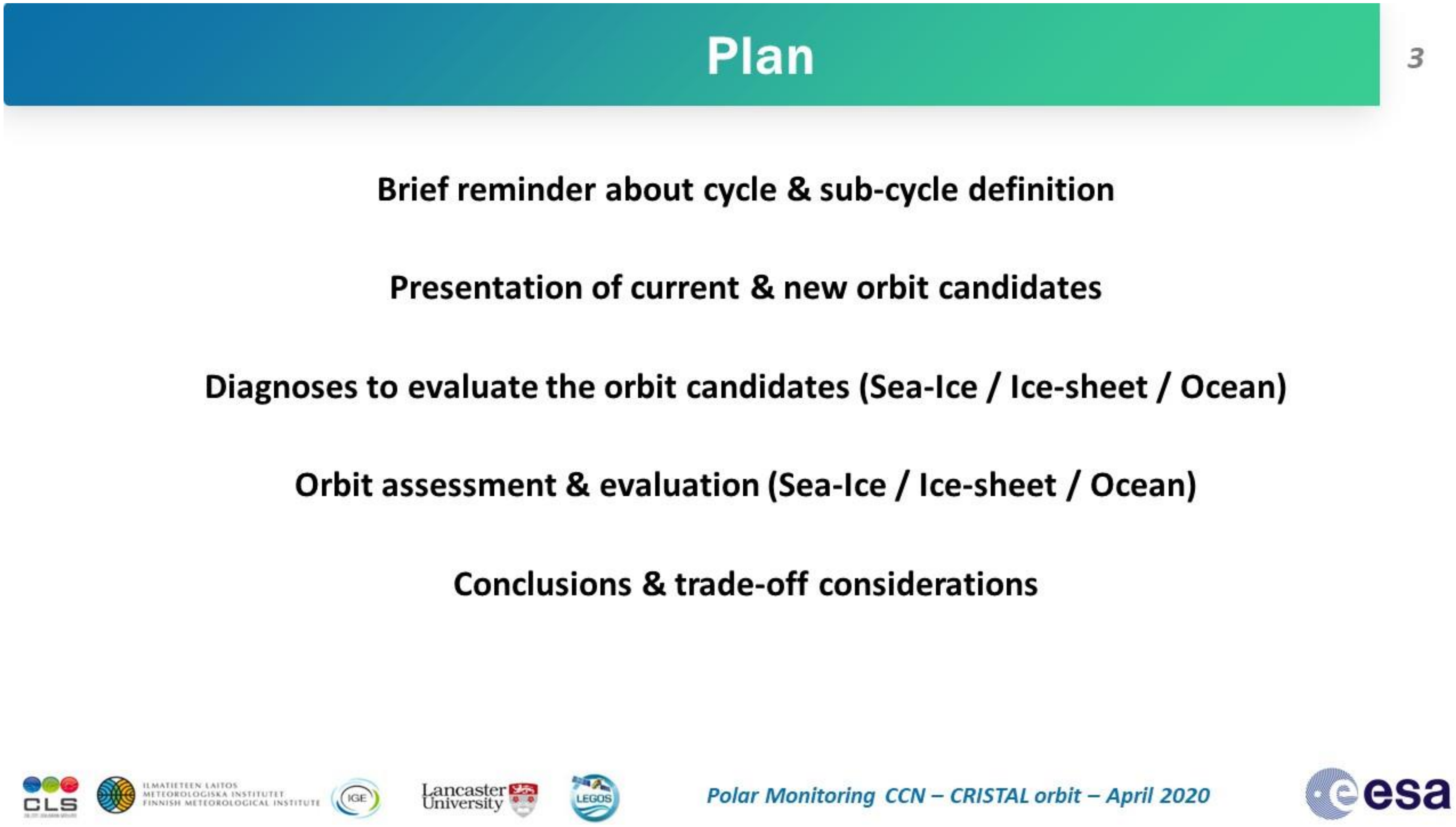
E.Rinne (FMI)

Polar Monitoring CCN – CRISTAL orbit – April 2020



Introduction

M.Kern - ESA - introduction



Plan

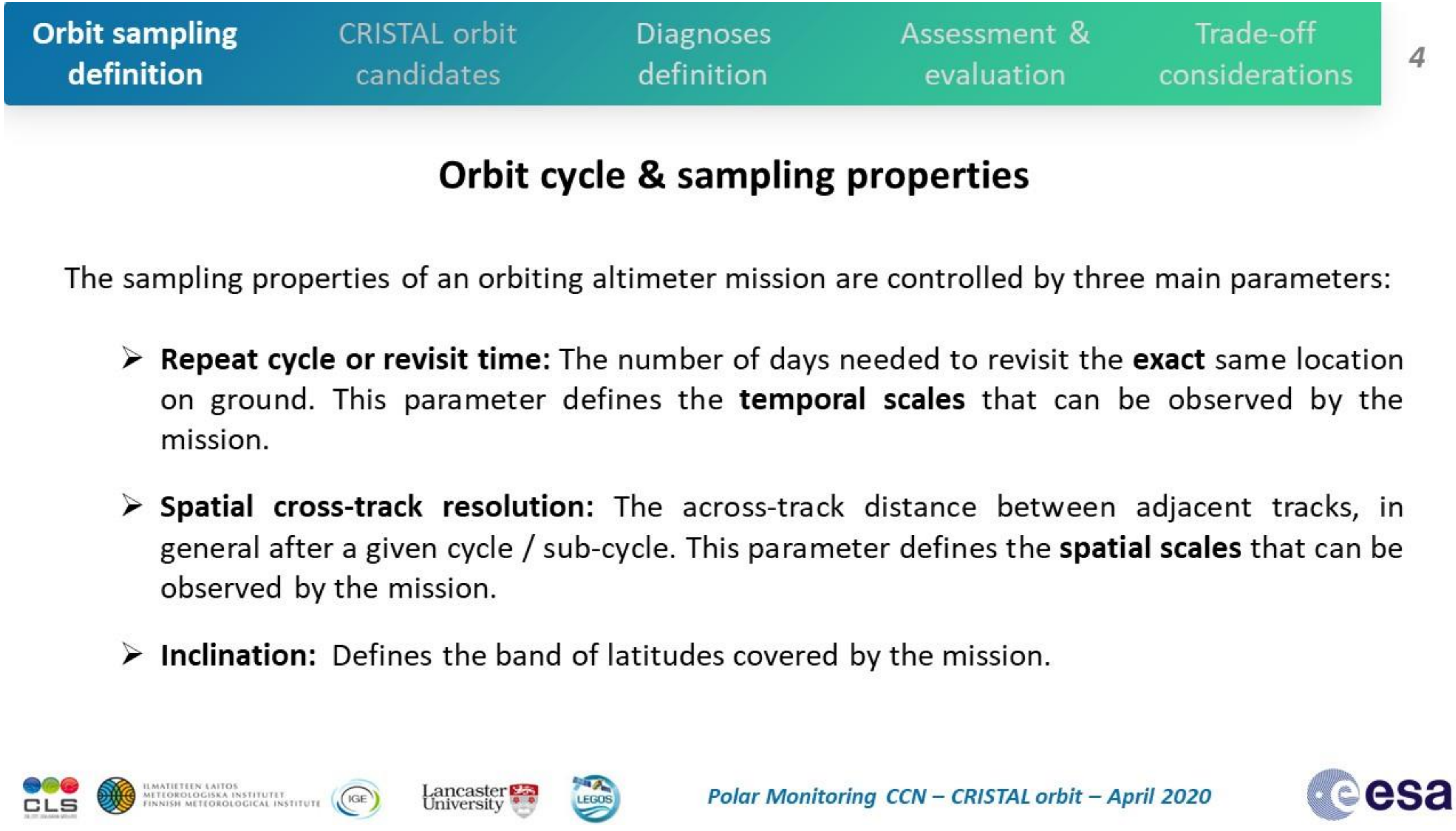
Brief reminder about cycle & sub-cycle definition

Presentation of current & new orbit candidates

Diagnoses to evaluate the orbit candidates (Sea-Ice / Ice-sheet / Ocean)

Orbit assessment & evaluation (Sea-Ice / Ice-sheet / Ocean)

Conclusions & trade-off considerations

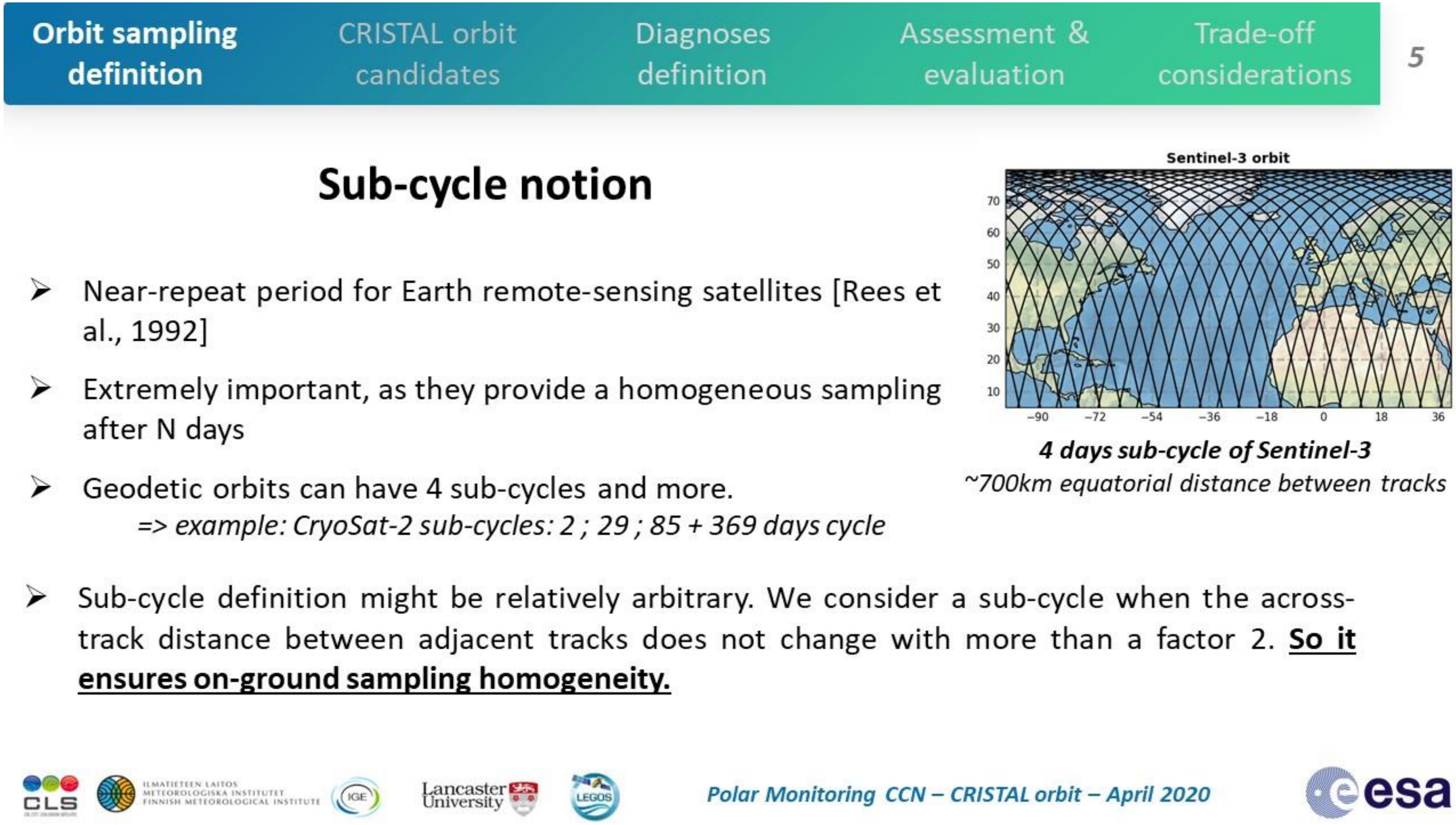


Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | Assessment & evaluation | Trade-off considerations

Orbit cycle & sampling properties

The sampling properties of an orbiting altimeter mission are controlled by three main parameters:

- **Repeat cycle or revisit time:** The number of days needed to revisit the **exact** same location on ground. This parameter defines the **temporal scales** that can be observed by the mission.
- **Spatial cross-track resolution:** The across-track distance between adjacent tracks, in general after a given cycle / sub-cycle. This parameter defines the **spatial scales** that can be observed by the mission.
- **Inclination:** Defines the band of latitudes covered by the mission.



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | Assessment & evaluation | Trade-off considerations

5

Sub-cycle notion

- ➢ Near-repeat period for Earth remote-sensing satellites [Rees et al., 1992]
- ➢ Extremely important, as they provide a homogeneous sampling after N days
- ➢ Geodetic orbits can have 4 sub-cycles and more.
  => example: CryoSat-2 sub-cycles: 2 ; 29 ; 85 + 369 days cycle

4 days sub-cycle of Sentinel-3

~700km equatorial distance between tracks

- ➢ Sub-cycle definition might be relatively arbitrary. We consider a sub-cycle when the across-track distance between adjacent tracks does not change with more than a factor 2. **So it ensures on-ground sampling homogeneity.**

Polar Monitoring CCN – CRISTAL orbit – April 2020

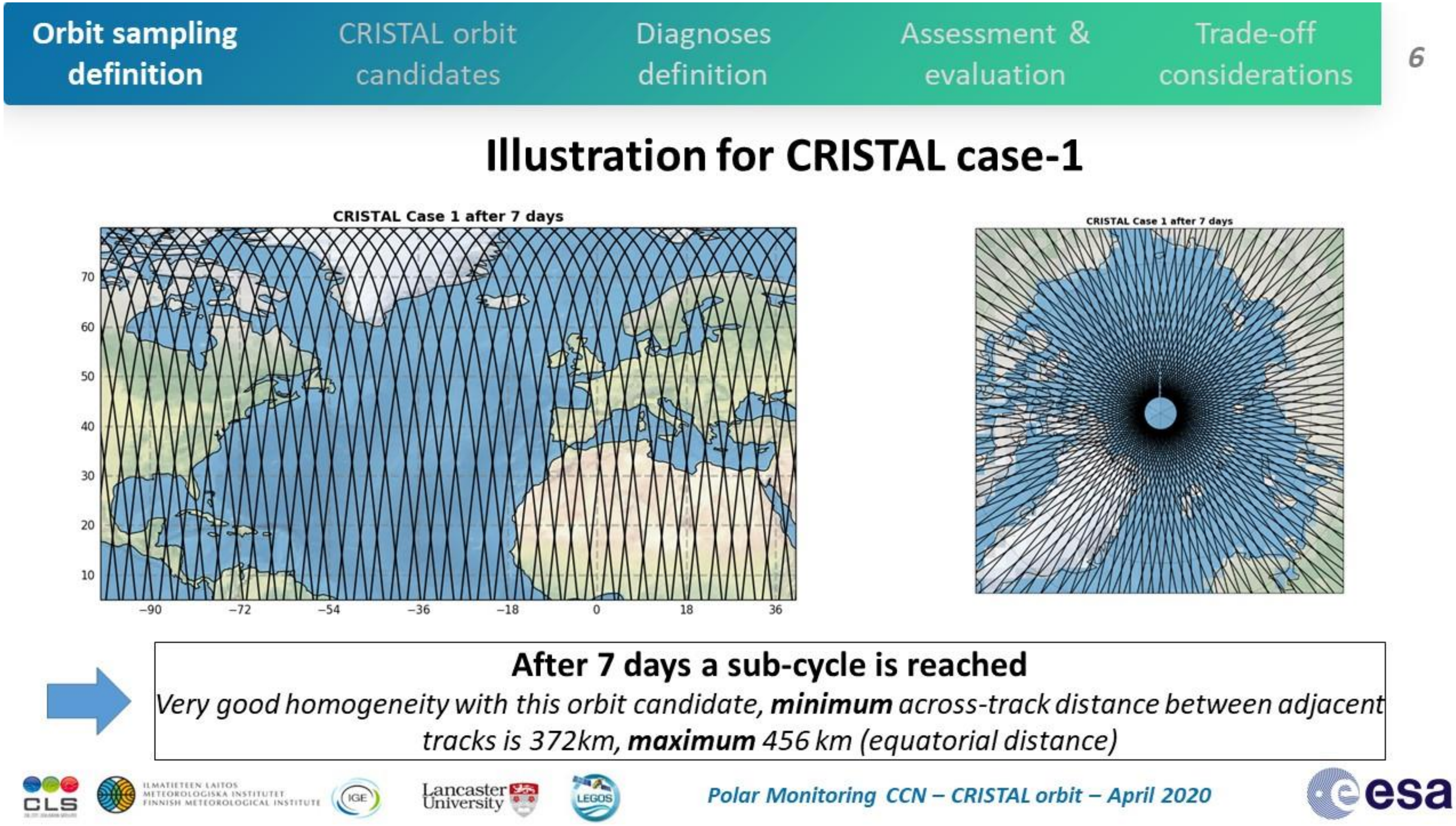
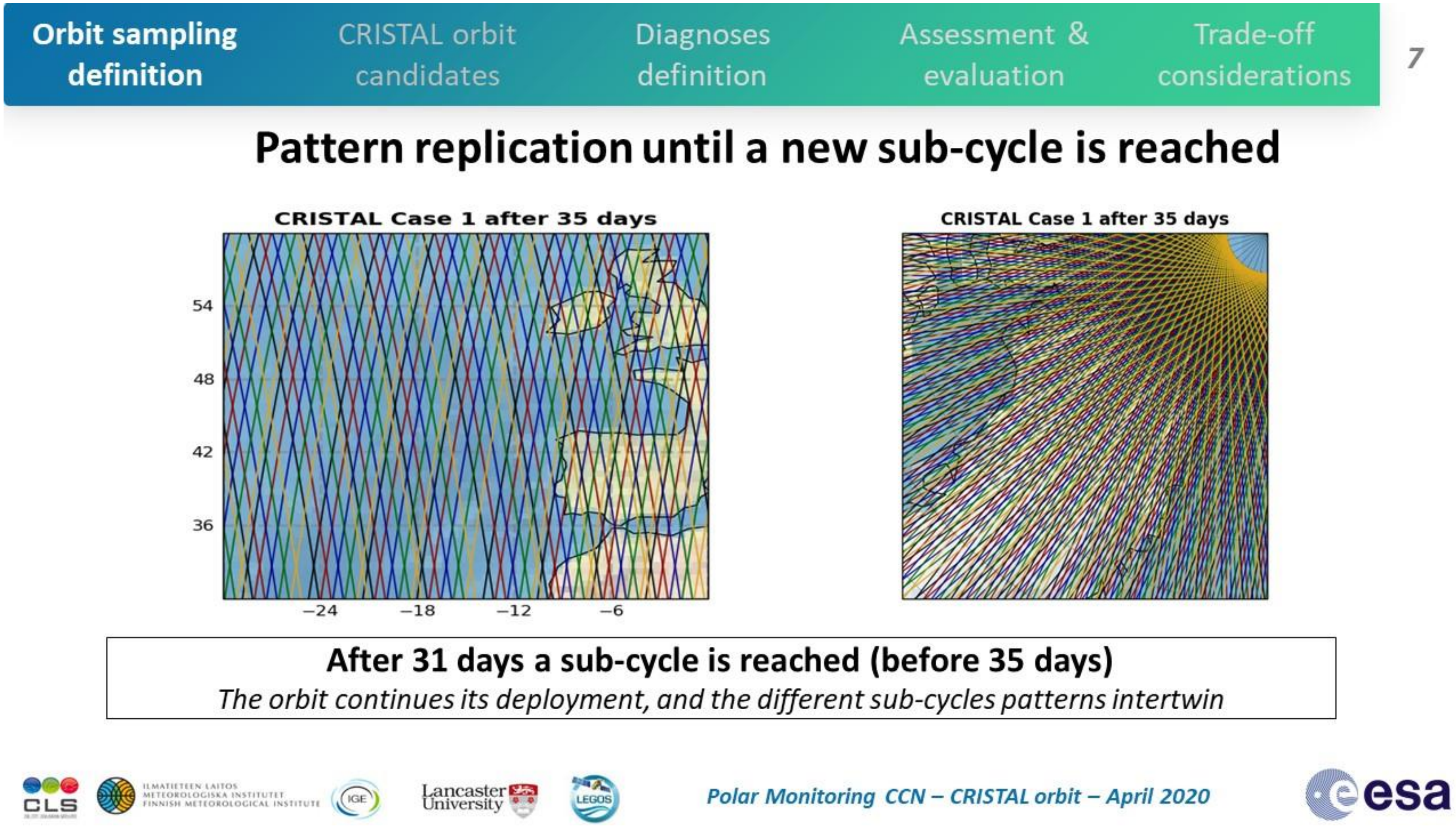


Illustration for CRISTAL case-1

After 7 days a sub-cycle is reached

Very good homogeneity with this orbit candidate, ***minimum*** *across-track distance between adjacent tracks is 372km,* ***maximum*** *456 km (equatorial distance)*



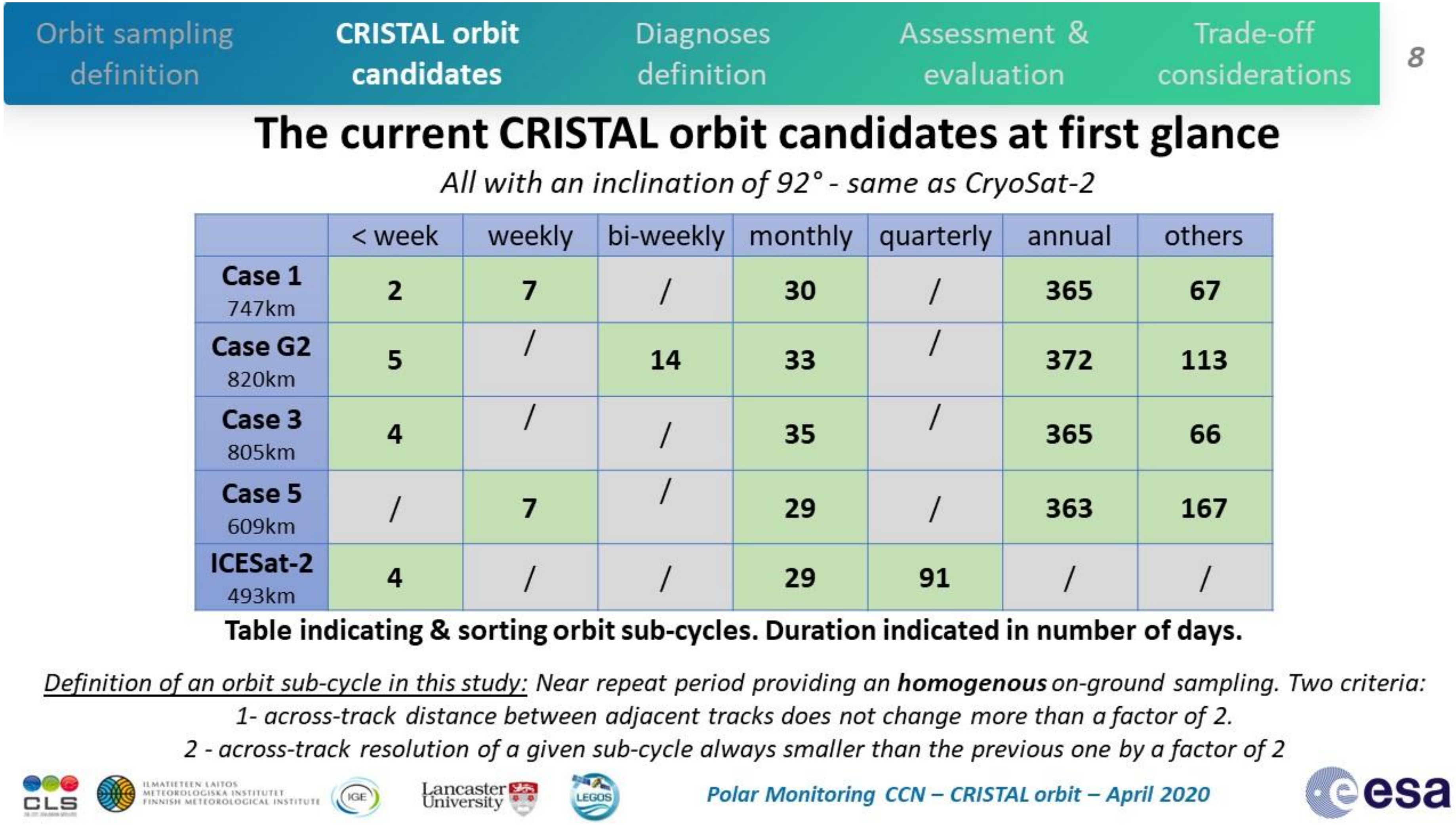
Pattern replication until a new sub-cycle is reached

CRISTAL Case 1 after 35 days

CRISTAL Case 1 after 35 days

After 31 days a sub-cycle is reached (before 35 days)

The orbit continues its deployment, and the different sub-cycles patterns intertwin



Orbit sampling definition | **CRISTAL orbit candidates** | Diagnoses definition | Assessment & evaluation | Trade-off considerations

8

The current CRISTAL orbit candidates at first glance

All with an inclination of 92° - same as CryoSat-2

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1 747km	**2**	**7**	/	**30**	/	**365**	**67**
Case G2 820km	**5**	/	**14**	**33**	/	**372**	**113**
Case 3 805km	**4**	/	/	**35**	/	**365**	**66**
Case 5 609km	/	**7**	/	**29**	/	**363**	**167**
ICESat-2 493km	**4**	/	/	**29**	**91**	/	/

Table indicating & sorting orbit sub-cycles. Duration indicated in number of days.

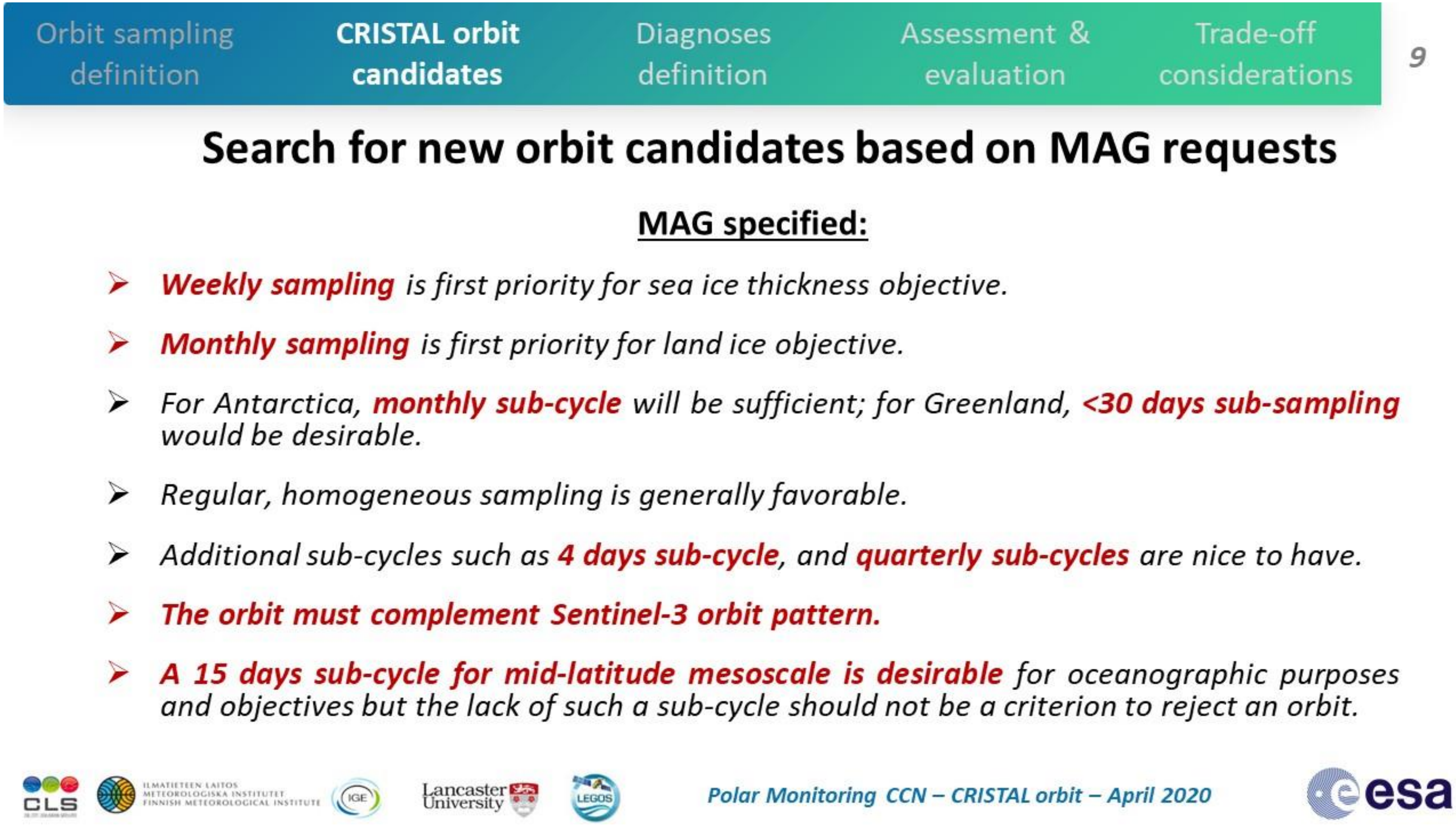
*Definition of an orbit sub-cycle in this study: Near repeat period providing an **homogenous** on-ground sampling. Two criteria:*

1- across-track distance between adjacent tracks does not change more than a factor of 2.

2 - across-track resolution of a given sub-cycle always smaller than the previous one by a factor of 2

Polar Monitoring CCN – CRISTAL orbit – April 2020

FORM-NT-GB-7-1

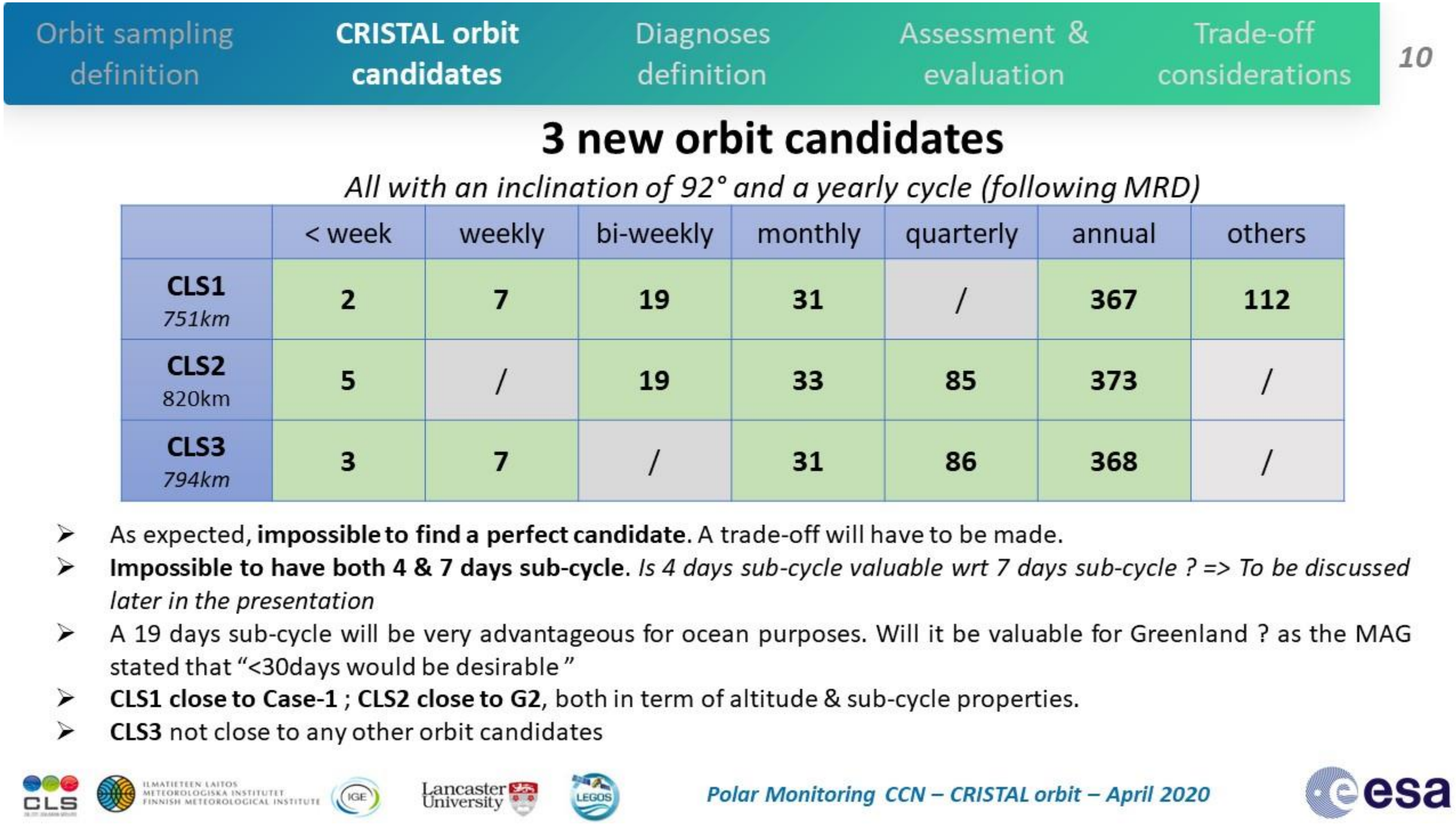


Orbit sampling definition | **CRISTAL orbit candidates** | Diagnoses definition | Assessment & evaluation | Trade-off considerations

Search for new orbit candidates based on MAG requests

MAG specified:

- ***Weekly sampling*** *is first priority for sea ice thickness objective.*
- ***Monthly sampling*** *is first priority for land ice objective.*
- *For Antarctica,* ***monthly sub-cycle*** *will be sufficient; for Greenland,* ***<30 days sub-sampling*** *would be desirable.*
- *Regular, homogeneous sampling is generally favorable.*
- *Additional sub-cycles such as* ***4 days sub-cycle****, and* ***quarterly sub-cycles*** *are nice to have.*
- ***The orbit must complement Sentinel-3 orbit pattern.***
- ***A 15 days sub-cycle for mid-latitude mesoscale is desirable*** *for oceanographic purposes and objectives but the lack of such a sub-cycle should not be a criterion to reject an orbit.*



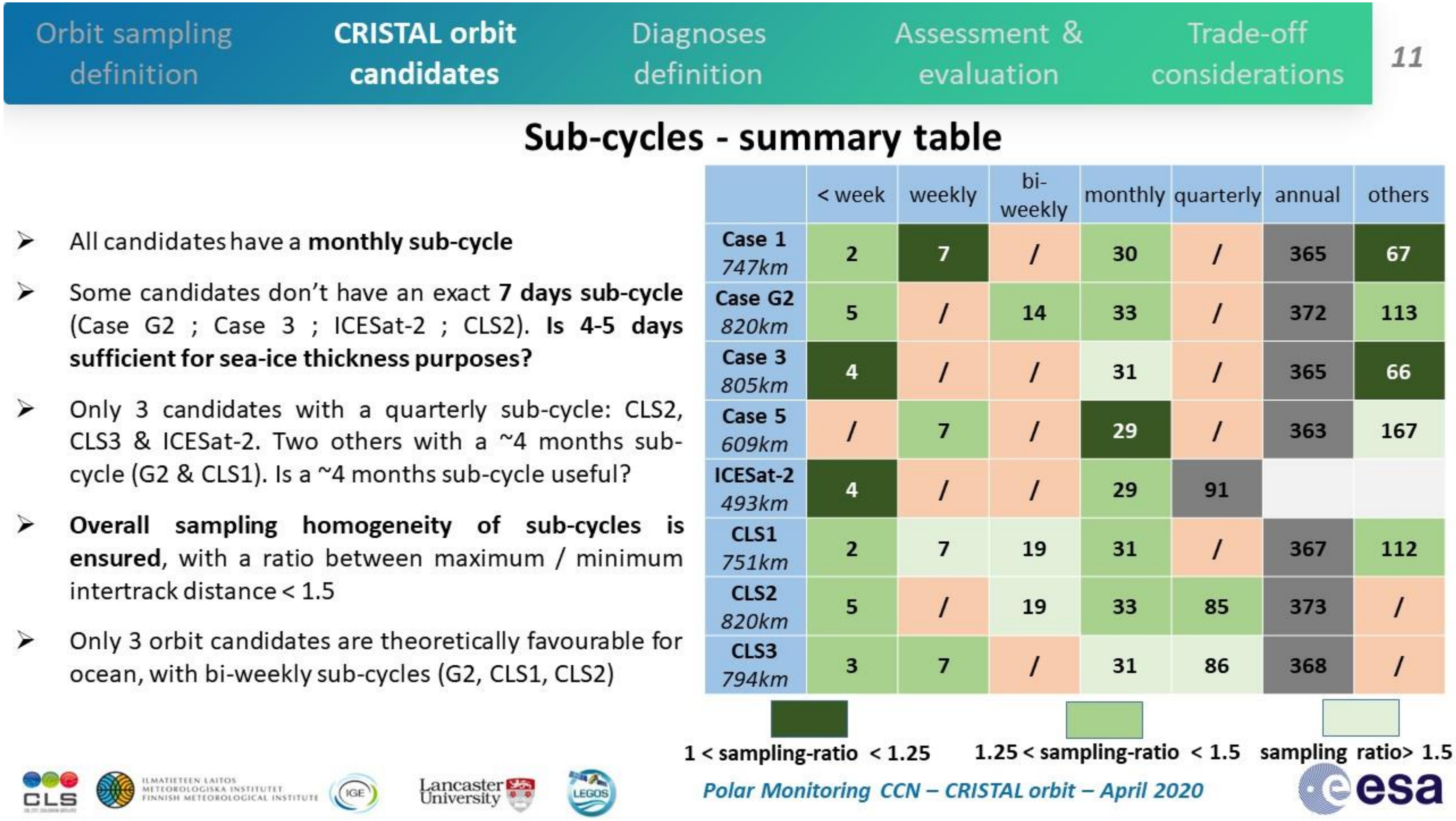
3 new orbit candidates

All with an inclination of 92° and a yearly cycle (following MRD)

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
CLS1 *751km*	**2**	**7**	**19**	**31**	/	**367**	**112**
CLS2 820km	**5**	/	**19**	**33**	**85**	**373**	/
CLS3 *794km*	**3**	**7**	/	**31**	**86**	**368**	/

- As expected, **impossible to find a perfect candidate**. A trade-off will have to be made.
- **Impossible to have both 4 & 7 days sub-cycle**. *Is 4 days sub-cycle valuable wrt 7 days sub-cycle ? => To be discussed later in the presentation*
- A 19 days sub-cycle will be very advantageous for ocean purposes. Will it be valuable for Greenland ? as the MAG stated that "<30days would be desirable"
- **CLS1 close to Case-1 ; CLS2 close to G2**, both in term of altitude & sub-cycle properties.
- **CLS3** not close to any other orbit candidates

Polar Monitoring CCN – CRISTAL orbit – April 2020

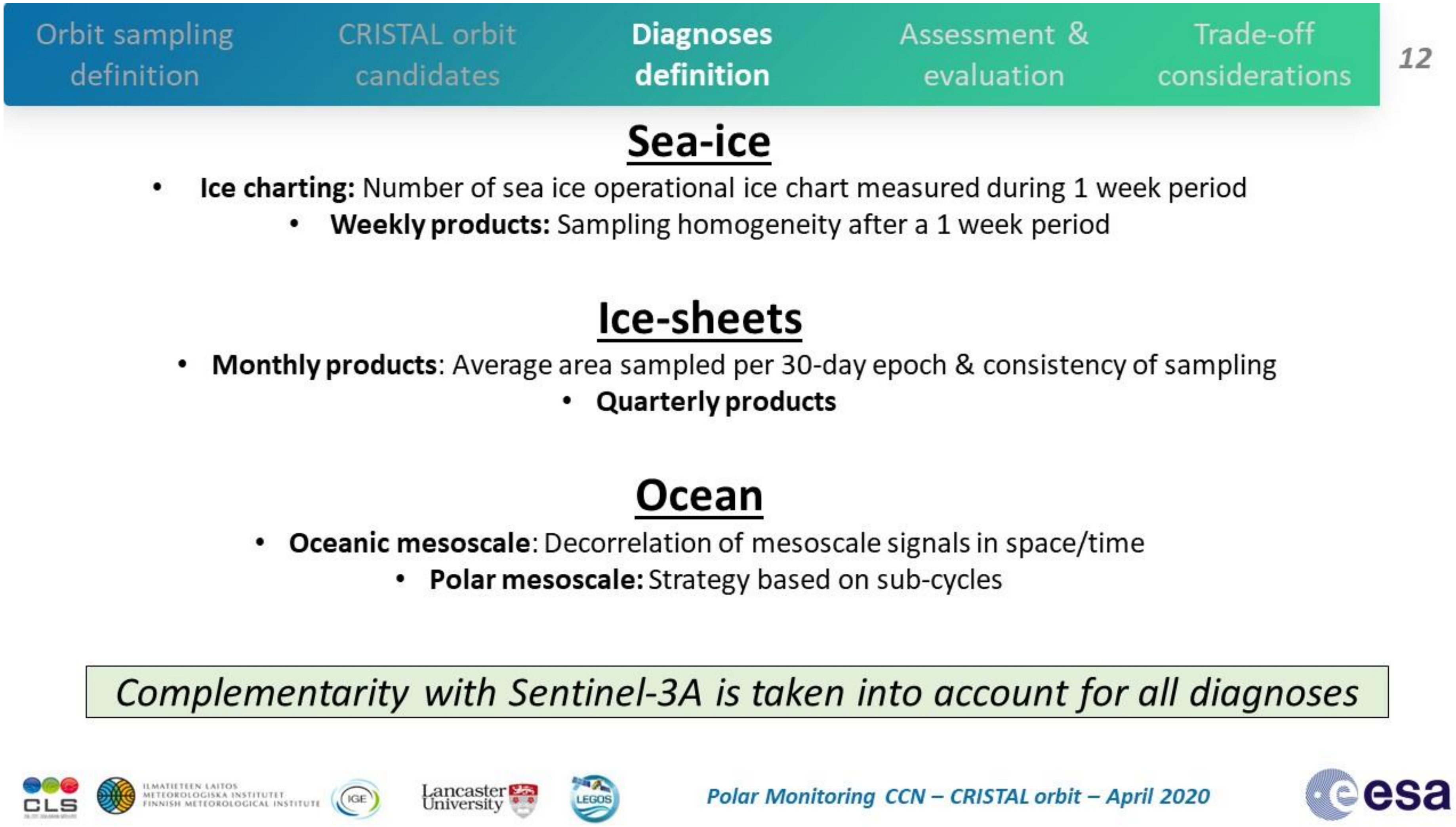


Sub-cycles - summary table

- All candidates have a **monthly sub-cycle**
- Some candidates don't have an exact **7 days sub-cycle** (Case G2 ; Case 3 ; ICESat-2 ; CLS2). **Is 4-5 days sufficient for sea-ice thickness purposes?**
- Only 3 candidates with a quarterly sub-cycle: CLS2, CLS3 & ICESat-2. Two others with a ~4 months sub-cycle (G2 & CLS1). Is a ~4 months sub-cycle useful?
- **Overall sampling homogeneity of sub-cycles is ensured**, with a ratio between maximum / minimum intertrack distance < 1.5
- Only 3 orbit candidates are theoretically favourable for ocean, with bi-weekly sub-cycles (G2, CLS1, CLS2)

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1 *747km*	2	7	/	30	/	365	67
Case G2 *820km*	5	/	14	33	/	372	113
Case 3 *805km*	4	/	/	31	/	365	66
Case 5 *609km*	/	7	/	29	/	363	167
ICESat-2 *493km*	4	/	/	29	91		
CLS1 *751km*	2	7	19	31	/	367	112
CLS2 *820km*	5	/	19	33	85	373	/
CLS3 *794km*	3	7	/	31	86	368	/

1 < sampling-ratio < 1.25 **1.25 < sampling-ratio < 1.5** **sampling ratio> 1.5**



Orbit sampling definition | CRISTAL orbit candidates | **Diagnoses definition** | Assessment & evaluation | Trade-off considerations

Sea-ice

- **Ice charting:** Number of sea ice operational ice chart measured during 1 week period
- **Weekly products:** Sampling homogeneity after a 1 week period

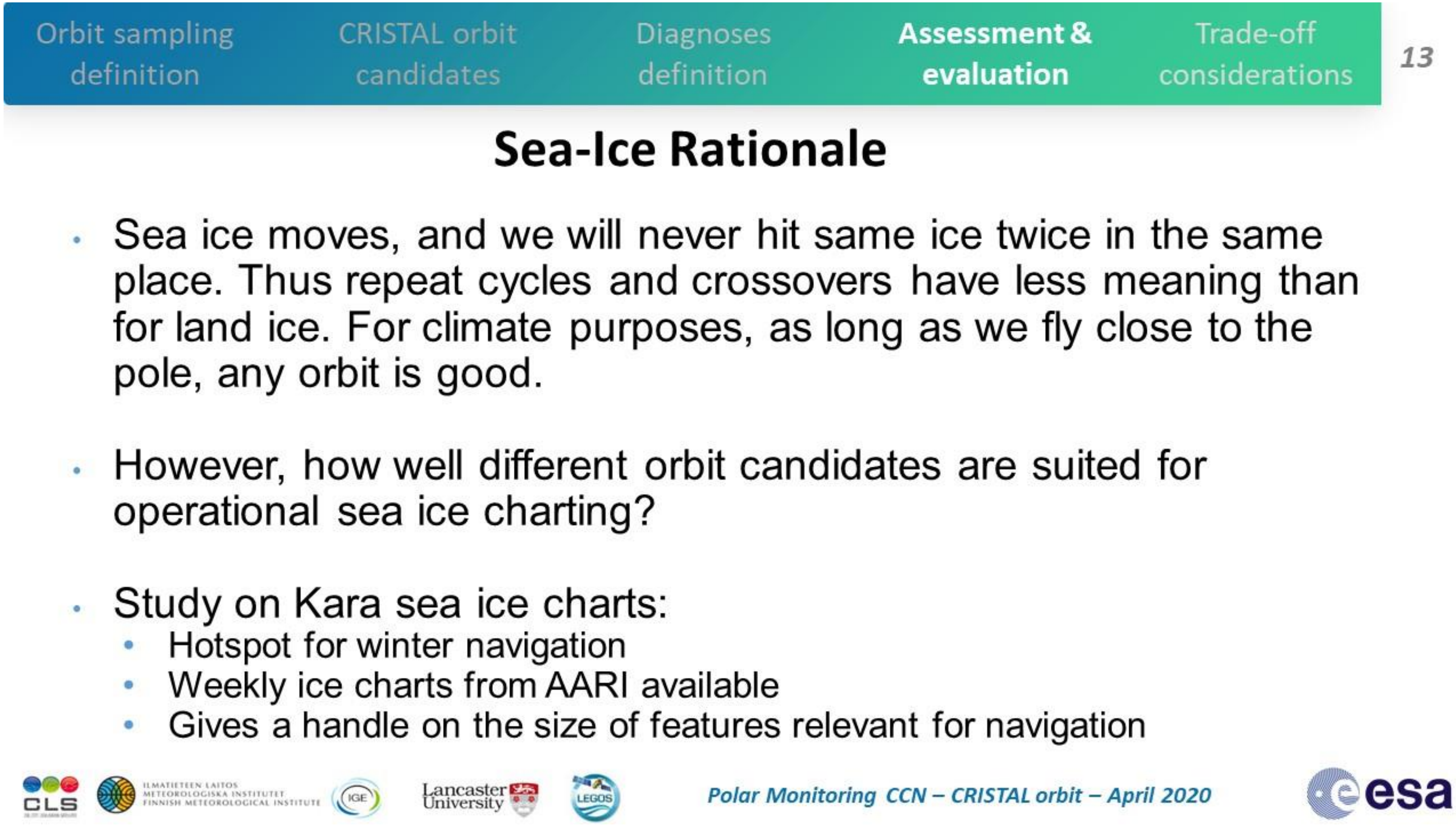
Ice-sheets

- **Monthly products**: Average area sampled per 30-day epoch & consistency of sampling
- **Quarterly products**

Ocean

- **Oceanic mesoscale**: Decorrelation of mesoscale signals in space/time
- **Polar mesoscale:** Strategy based on sub-cycles

Complementarity with Sentinel-3A is taken into account for all diagnoses



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

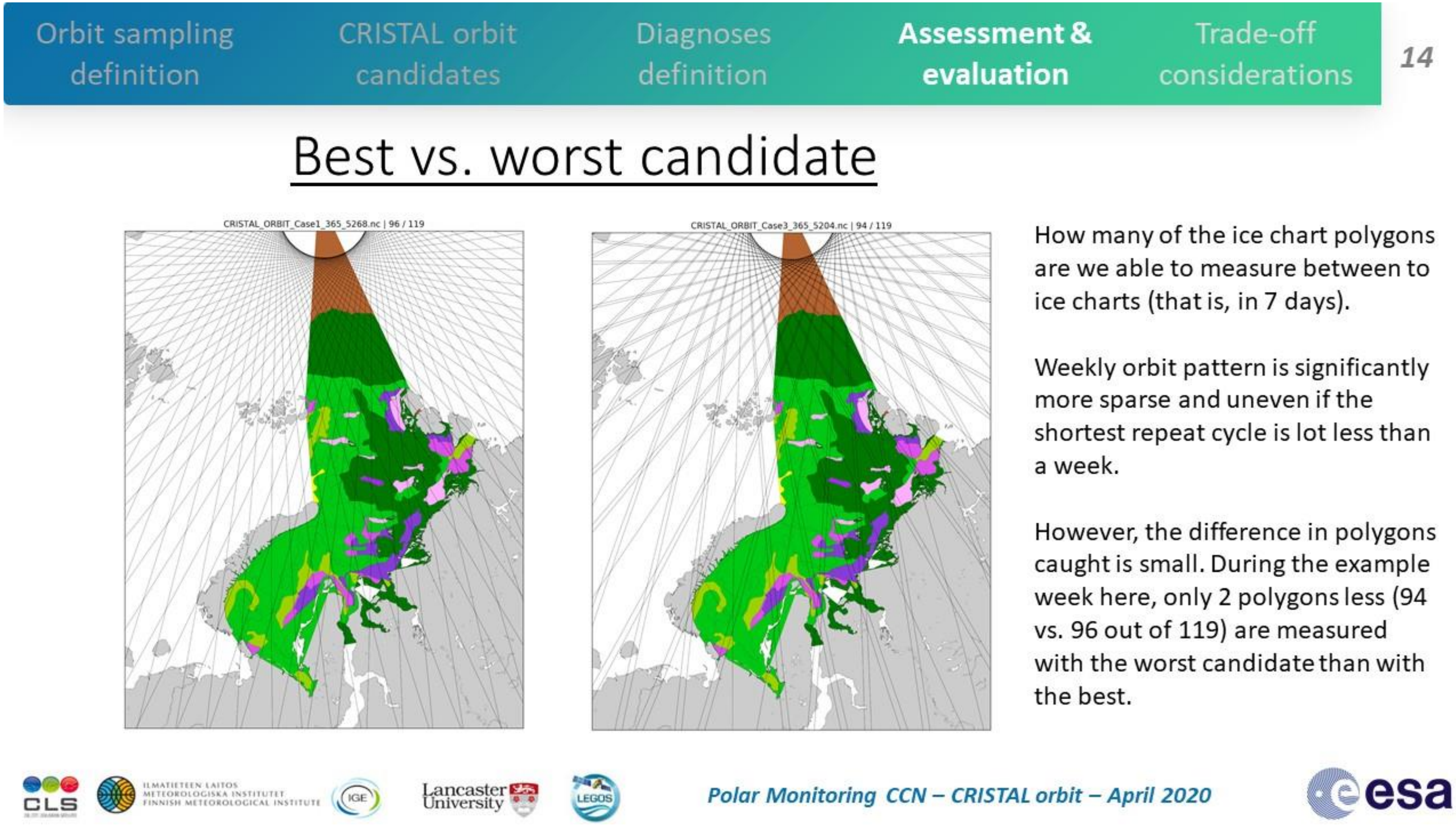
Sea-Ice Rationale

- Sea ice moves, and we will never hit same ice twice in the same place. Thus repeat cycles and crossovers have less meaning than for land ice. For climate purposes, as long as we fly close to the pole, any orbit is good.

- However, how well different orbit candidates are suited for operational sea ice charting?

- Study on Kara sea ice charts:
  - Hotspot for winter navigation
  - Weekly ice charts from AARI available
  - Gives a handle on the size of features relevant for navigation

Polar Monitoring CCN – CRISTAL orbit – April 2020

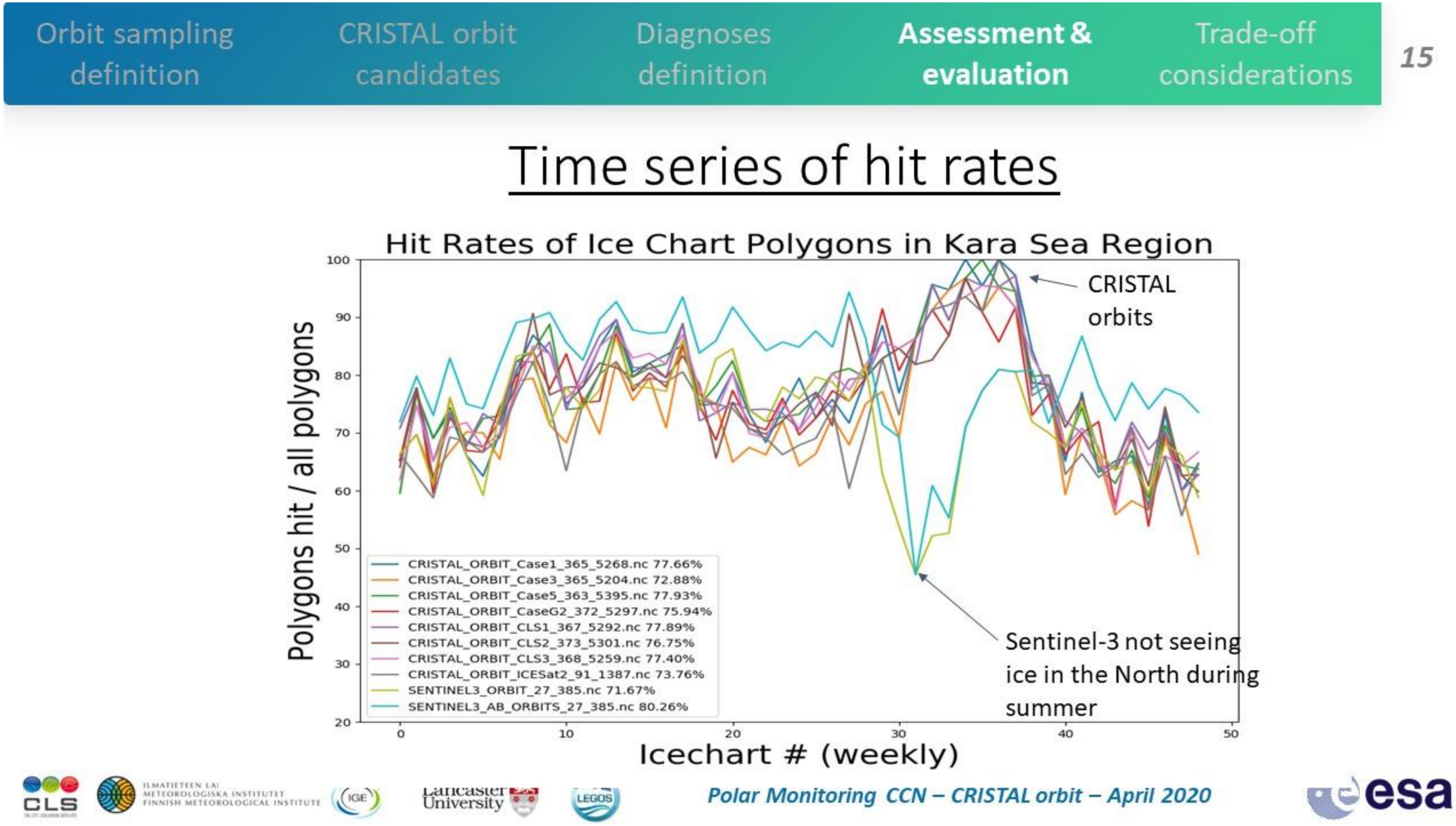


Best vs. worst candidate

How many of the ice chart polygons are we able to measure between to ice charts (that is, in 7 days).

Weekly orbit pattern is significantly more sparse and uneven if the shortest repeat cycle is lot less than a week.

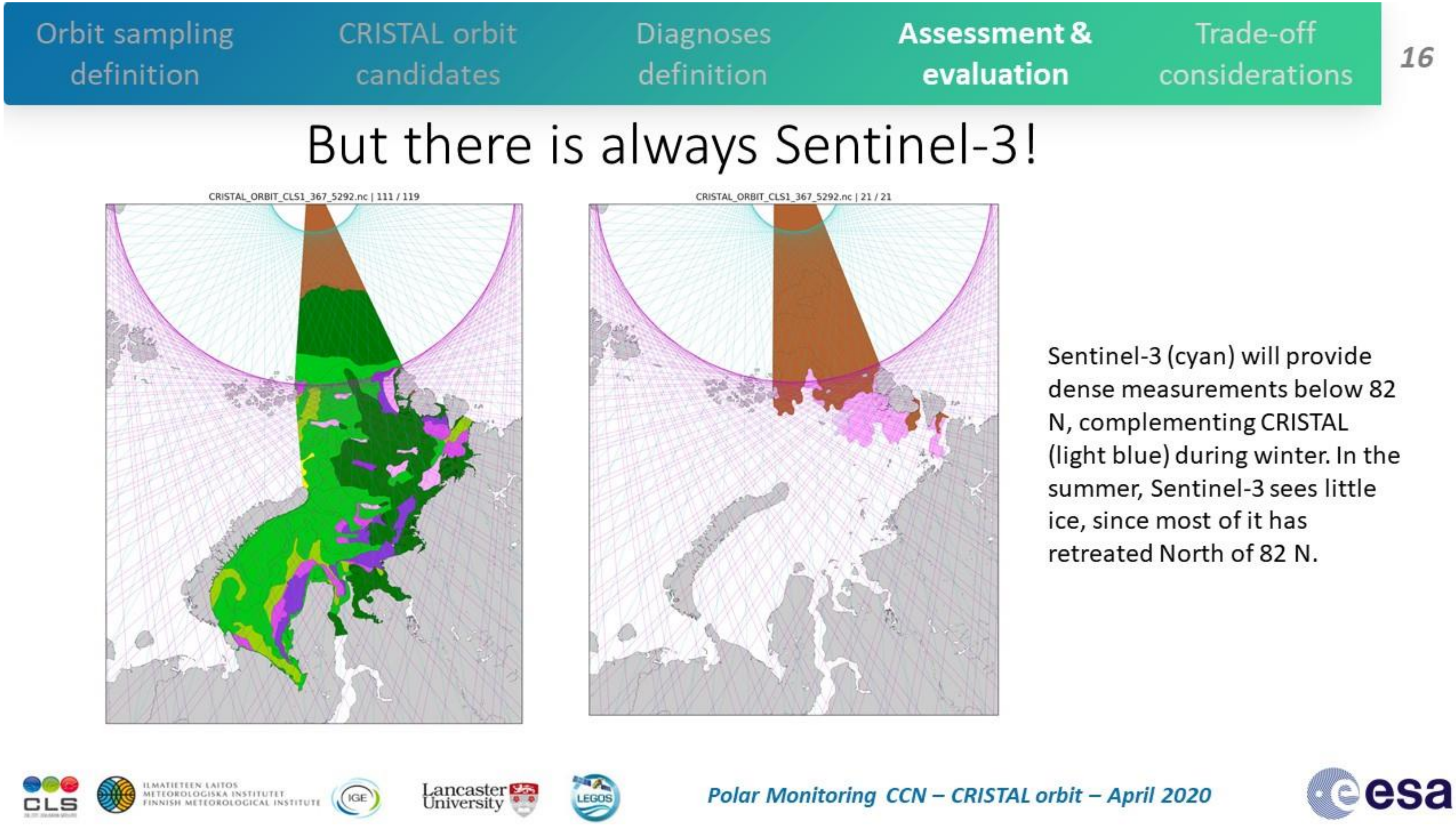
However, the difference in polygons caught is small. During the example week here, only 2 polygons less (94 vs. 96 out of 119) are measured with the worst candidate than with the best.



Time series of hit rates

CRISTAL orbits

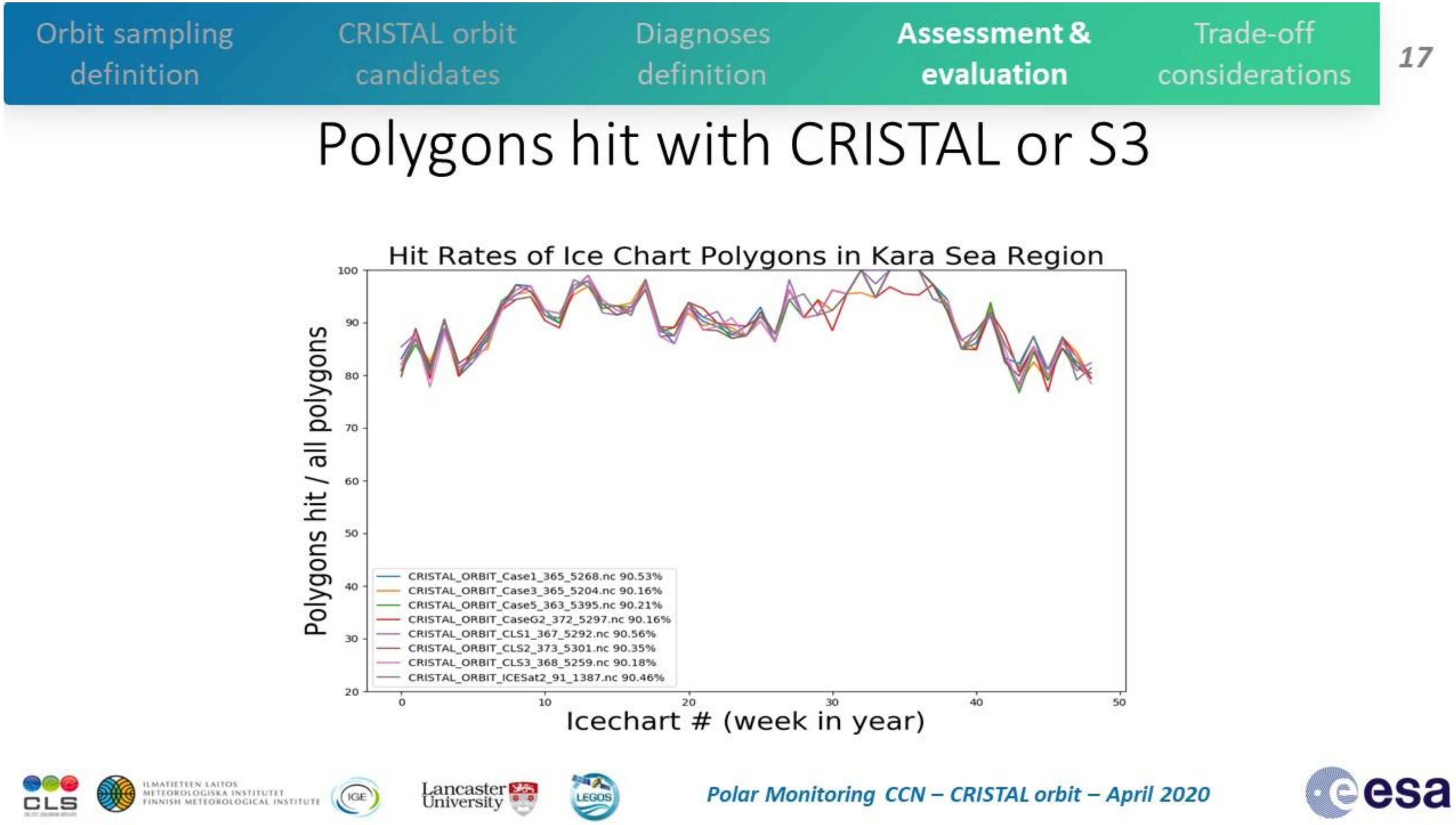
Sentinel-3 not seeing ice in the North during summer



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

But there is always Sentinel-3!

Sentinel-3 (cyan) will provide dense measurements below 82 N, complementing CRISTAL (light blue) during winter. In the summer, Sentinel-3 sees little ice, since most of it has retreated North of 82 N.



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

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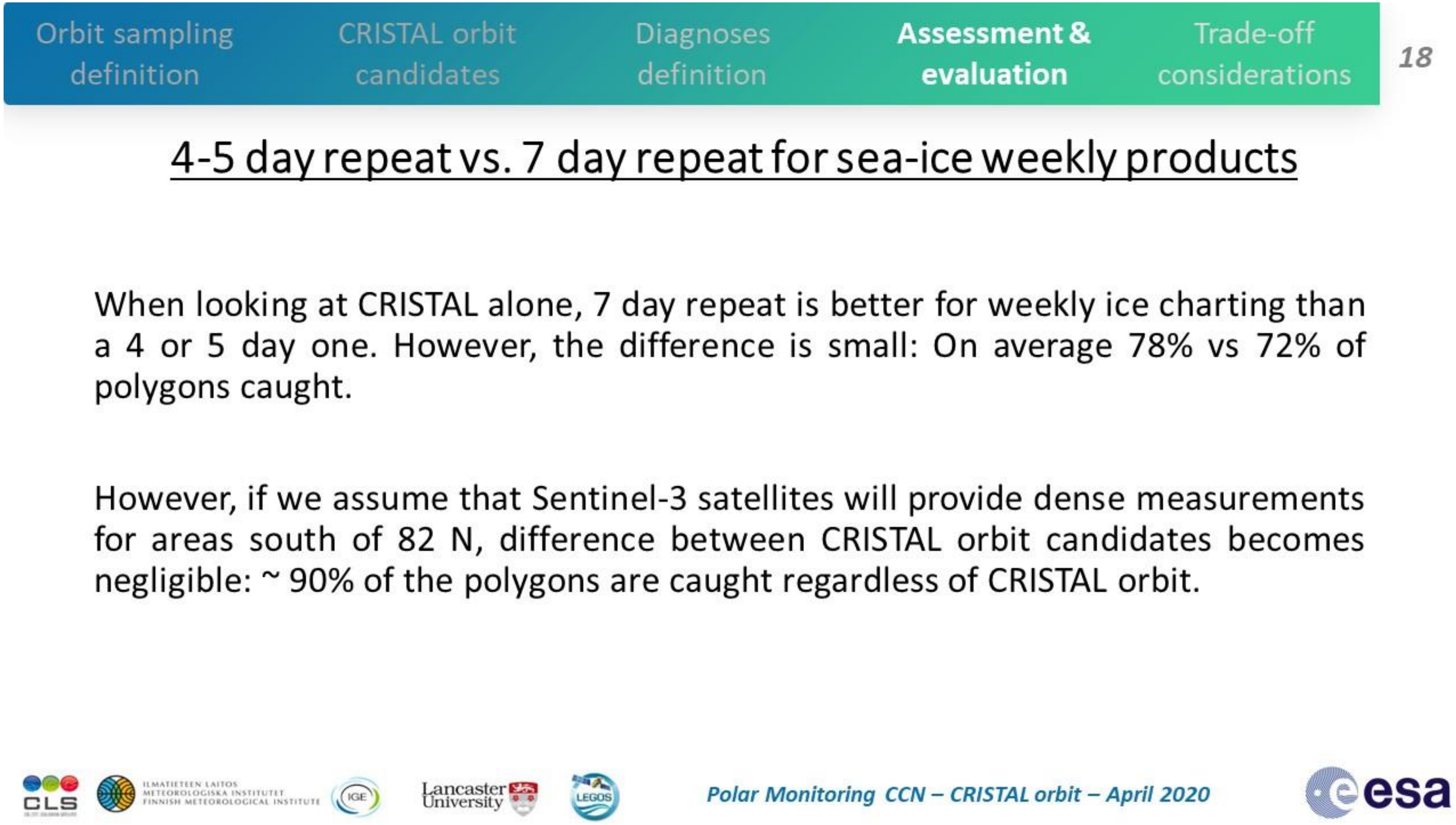
Polygons hit with CRISTAL or S3

Polar Monitoring CCN – CRISTAL orbit – April 2020

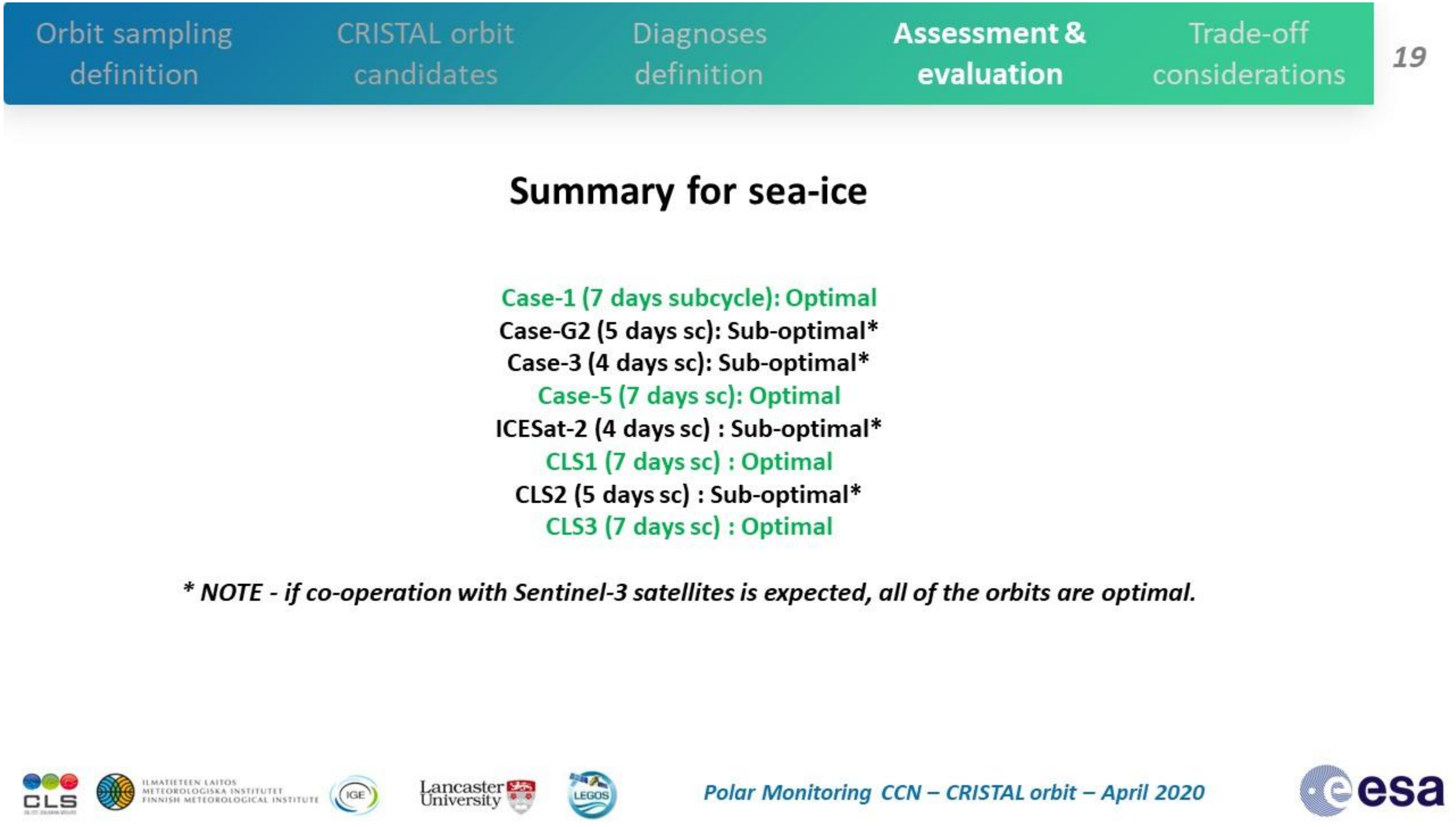


Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

4-5 day repeat vs. 7 day repeat for sea-ice weekly products

When looking at CRISTAL alone, 7 day repeat is better for weekly ice charting than a 4 or 5 day one. However, the difference is small: On average 78% vs 72% of polygons caught.

However, if we assume that Sentinel-3 satellites will provide dense measurements for areas south of 82 N, difference between CRISTAL orbit candidates becomes negligible: ~ 90% of the polygons are caught regardless of CRISTAL orbit.

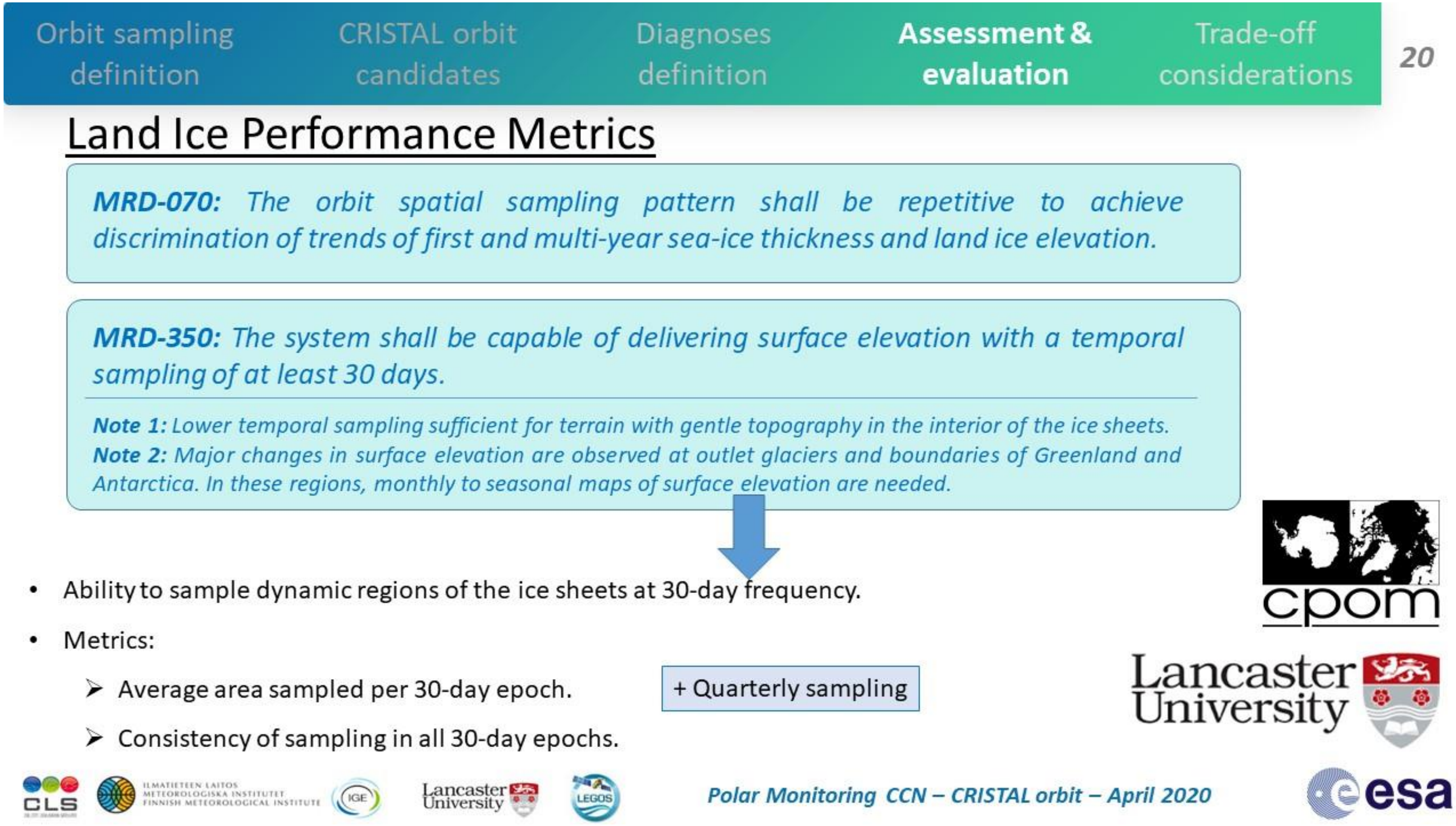


Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

Summary for sea-ice

Case-1 (7 days subcycle): Optimal
Case-G2 (5 days sc): Sub-optimal*
Case-3 (4 days sc): Sub-optimal*
Case-5 (7 days sc): Optimal
ICESat-2 (4 days sc) : Sub-optimal*
CLS1 (7 days sc) : Optimal
CLS2 (5 days sc) : Sub-optimal*
CLS3 (7 days sc) : Optimal

**** NOTE - if co-operation with Sentinel-3 satellites is expected, all of the orbits are optimal.***



Land Ice Performance Metrics

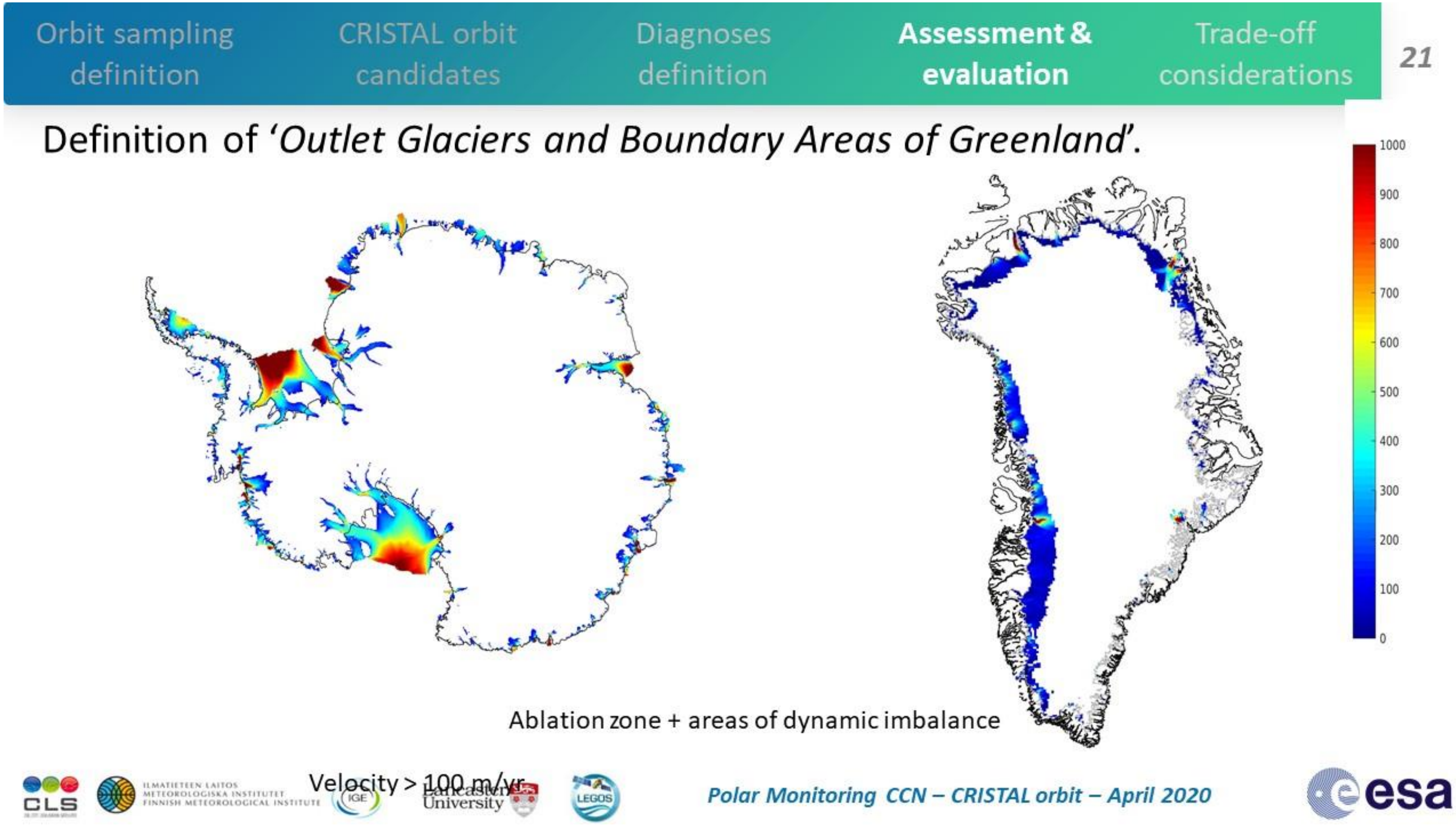
***MRD-070:** The orbit spatial sampling pattern shall be repetitive to achieve discrimination of trends of first and multi-year sea-ice thickness and land ice elevation.*

***MRD-350:** The system shall be capable of delivering surface elevation with a temporal sampling of at least 30 days.*

***Note 1:** Lower temporal sampling sufficient for terrain with gentle topography in the interior of the ice sheets.*
***Note 2:** Major changes in surface elevation are observed at outlet glaciers and boundaries of Greenland and Antarctica. In these regions, monthly to seasonal maps of surface elevation are needed.*

- Ability to sample dynamic regions of the ice sheets at 30-day frequency.
- Metrics:
  - Average area sampled per 30-day epoch.
  - Consistency of sampling in all 30-day epochs.

+ Quarterly sampling



Definition of '*Outlet Glaciers and Boundary Areas of Greenland*'.

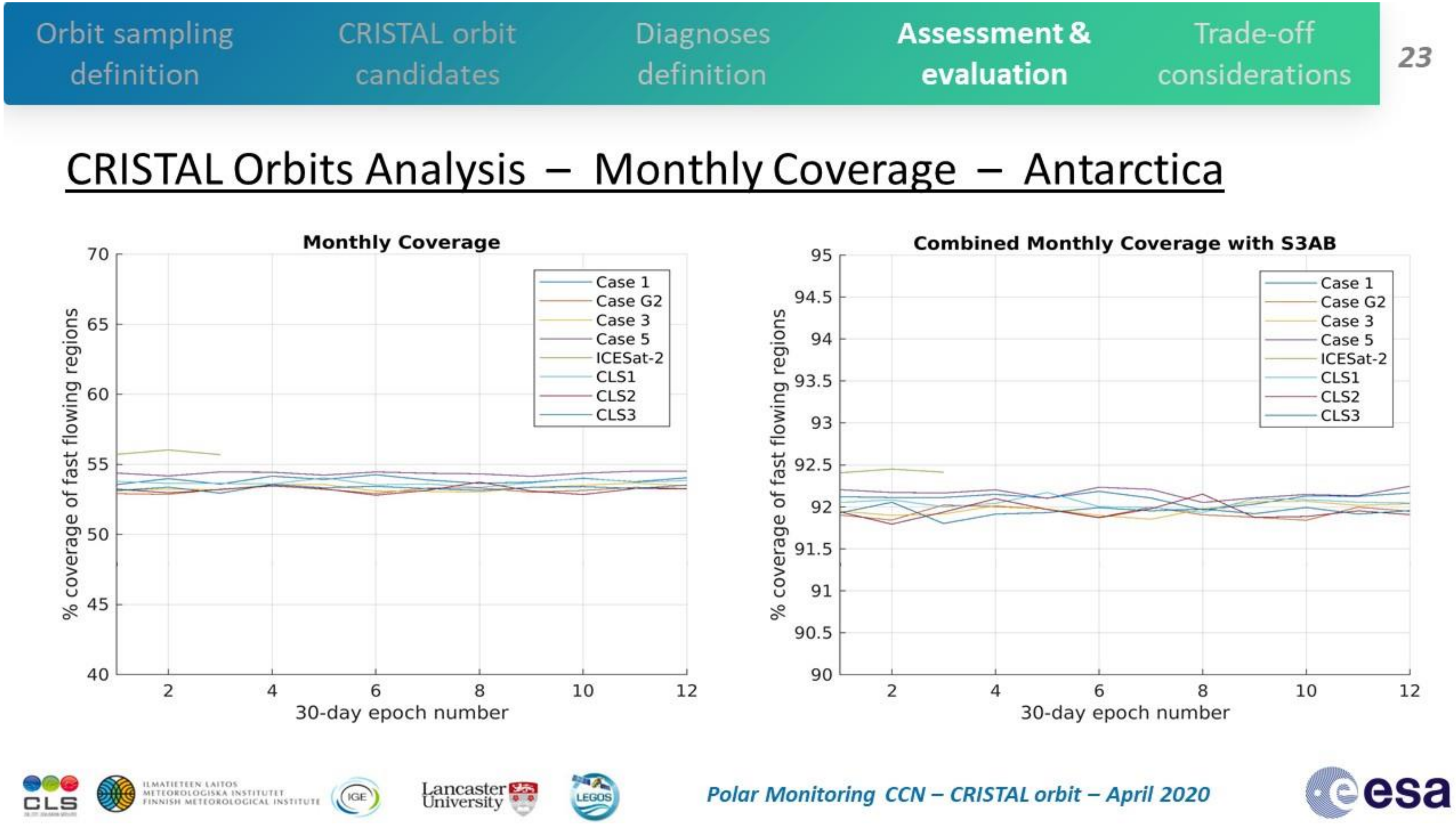
Ablation zone + areas of dynamic imbalance

Velocity > 100 m/yr

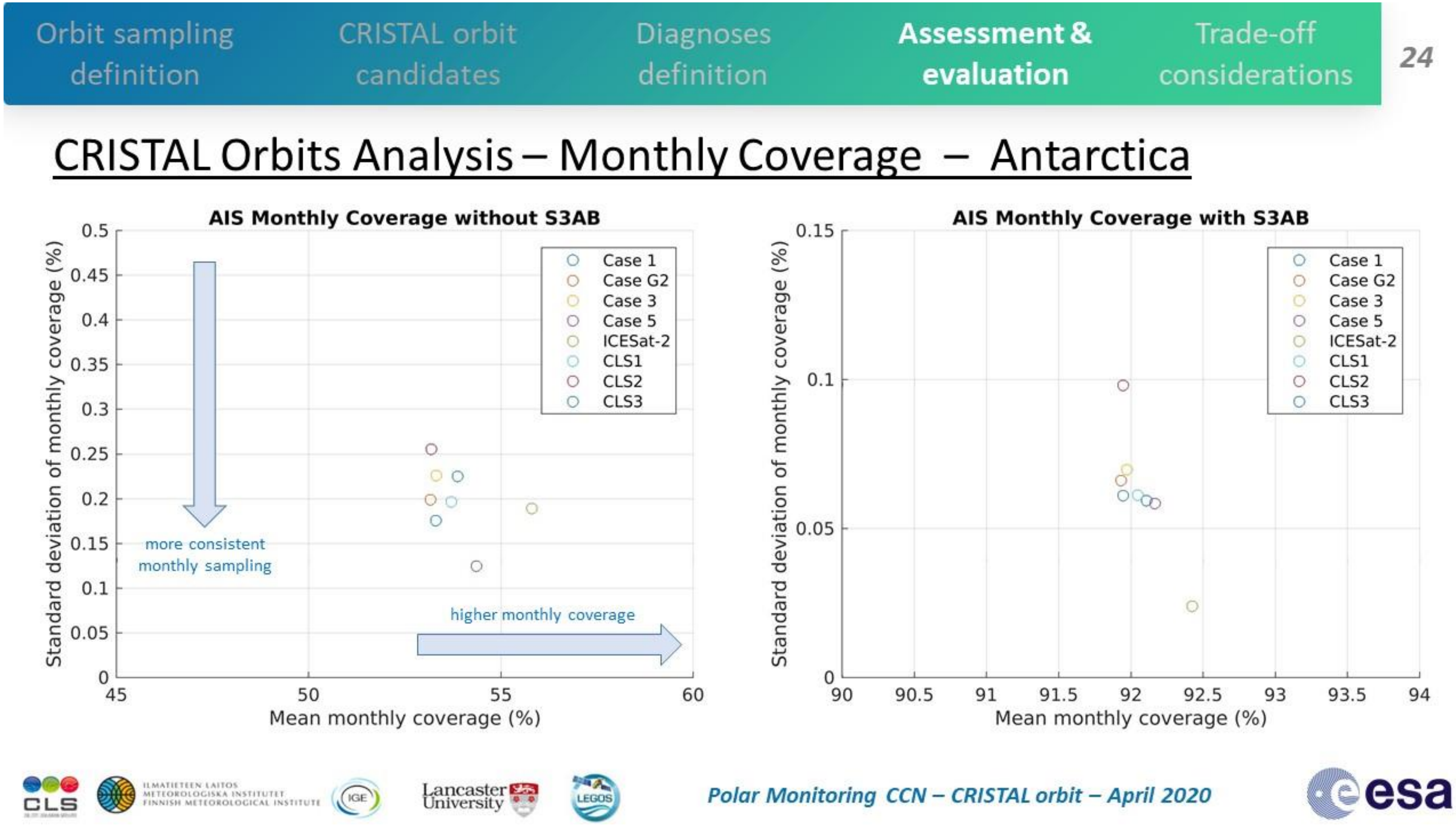
Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

Antarctica -- Monthly

Polar Monitoring CCN – CRISTAL orbit – April 2020

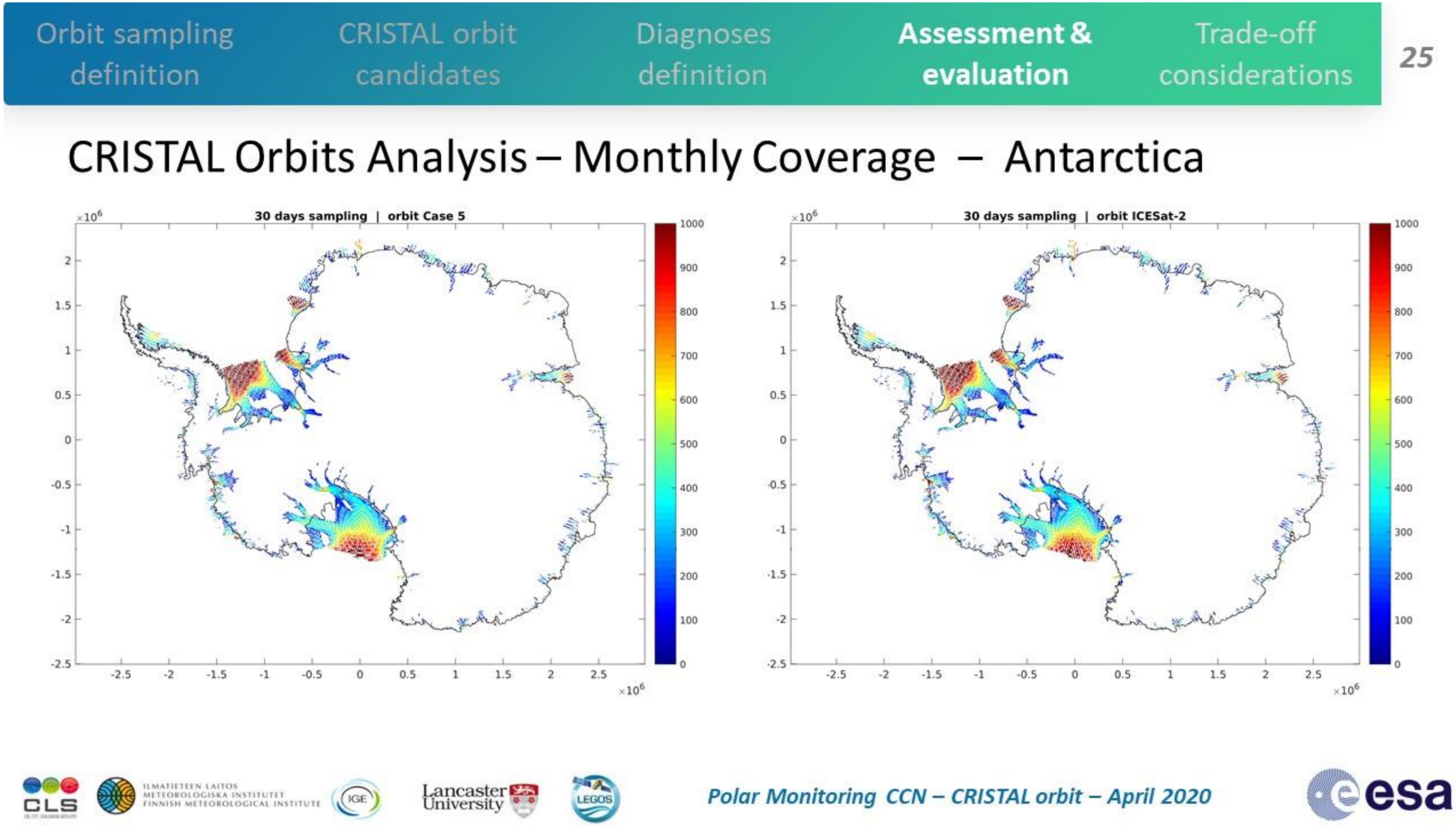


CRISTAL Orbits Analysis – Monthly Coverage – Antarctica



CRISTAL Orbits Analysis – Monthly Coverage – Antarctica

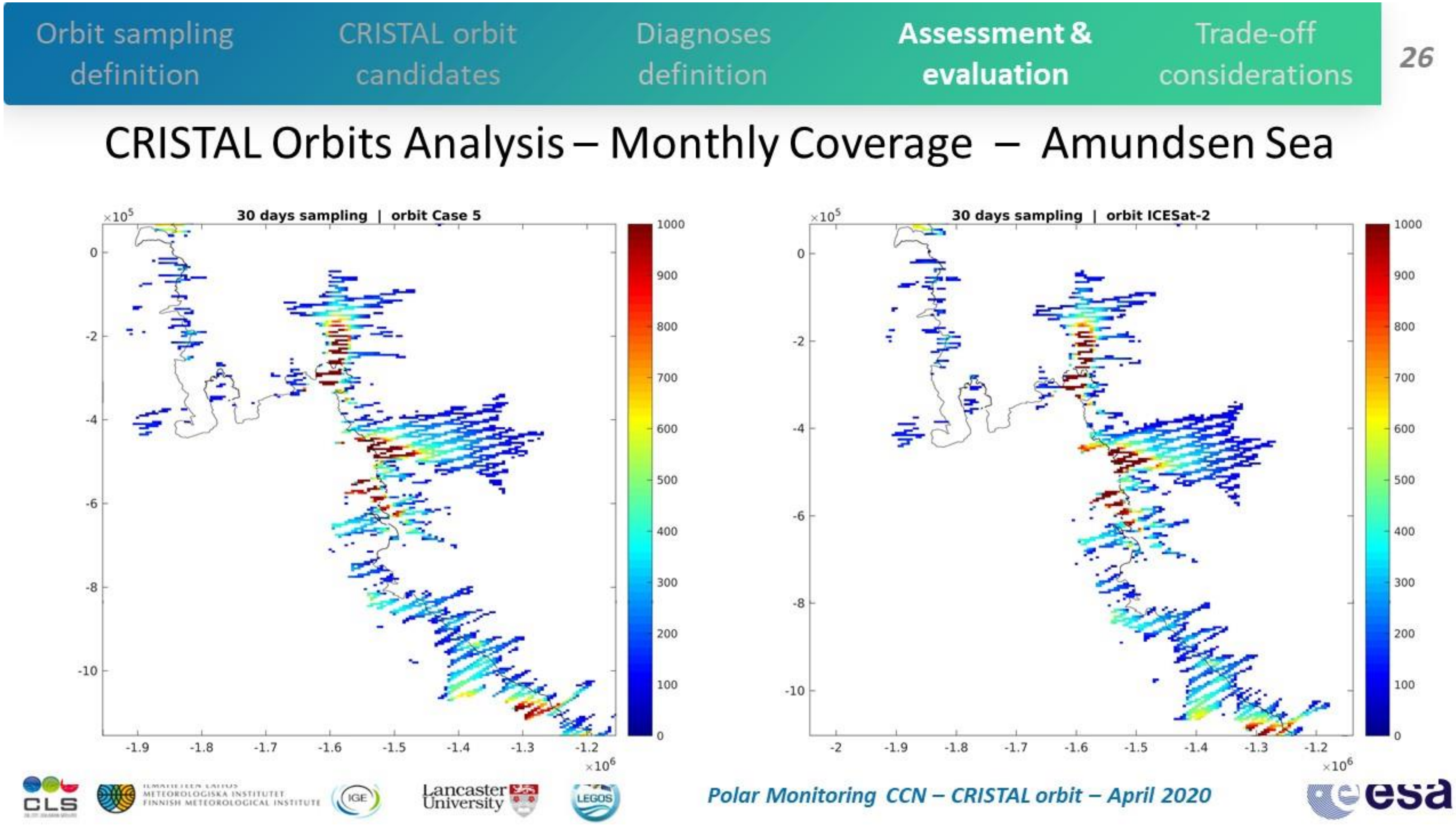
Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

CRISTAL Orbits Analysis – Monthly Coverage – Antarctica

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

CRISTAL Orbits Analysis – Monthly Coverage – Amundsen Sea

30 days sampling | orbit Case 5

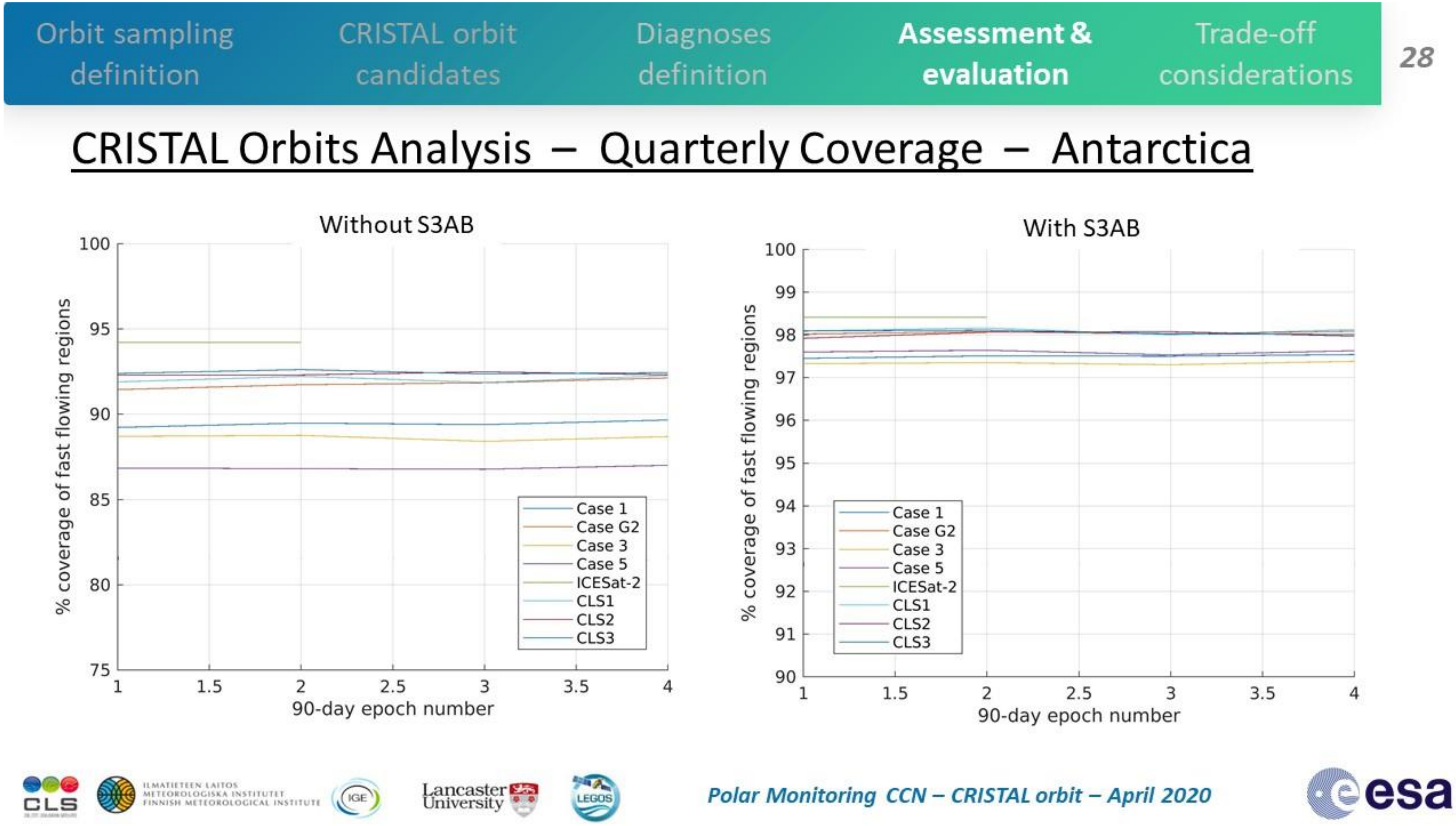
30 days sampling | orbit ICESat-2

Polar Monitoring CCN – CRISTAL orbit – April 2020

Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

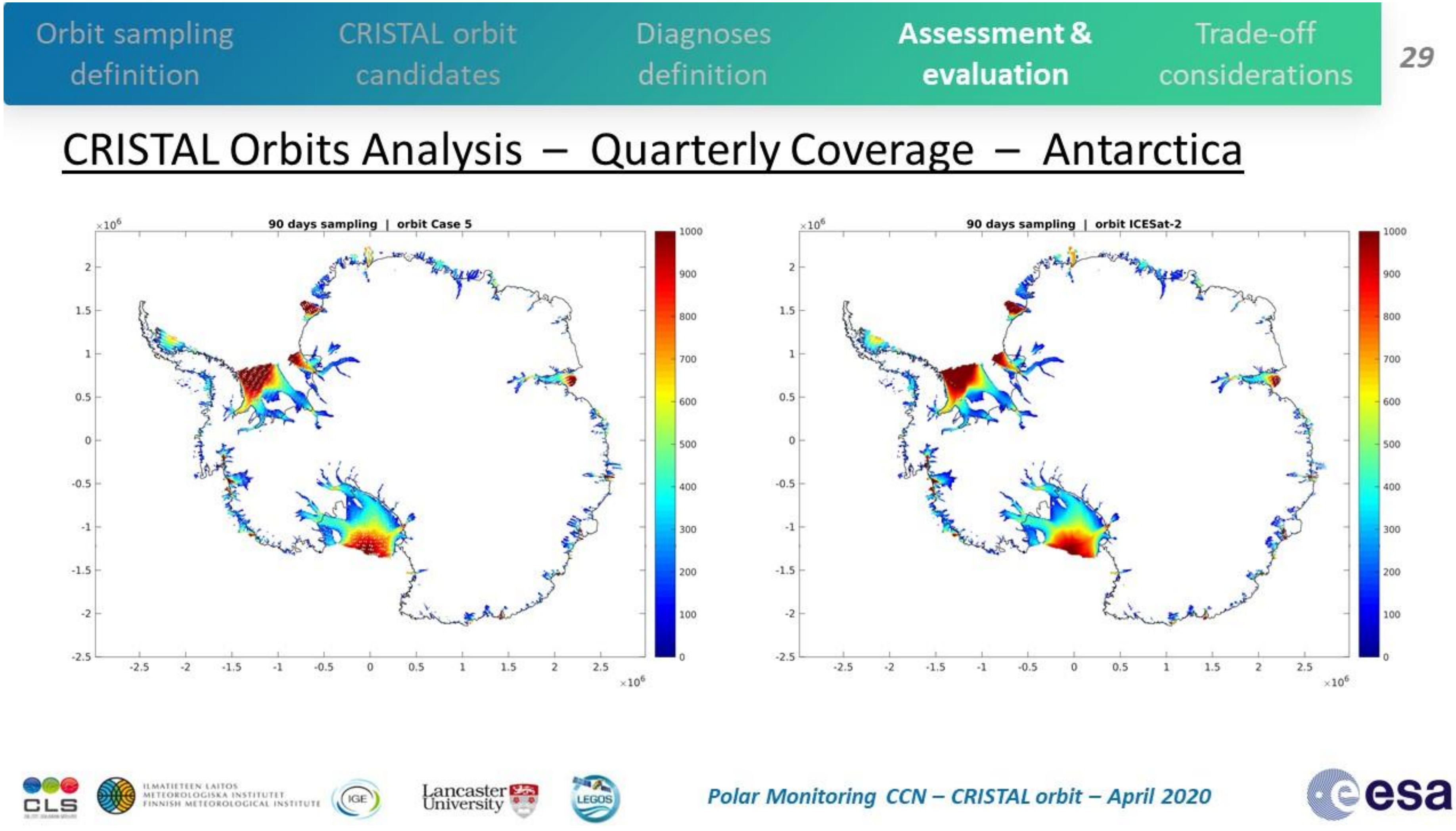
Antarctica -- Quarterly

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

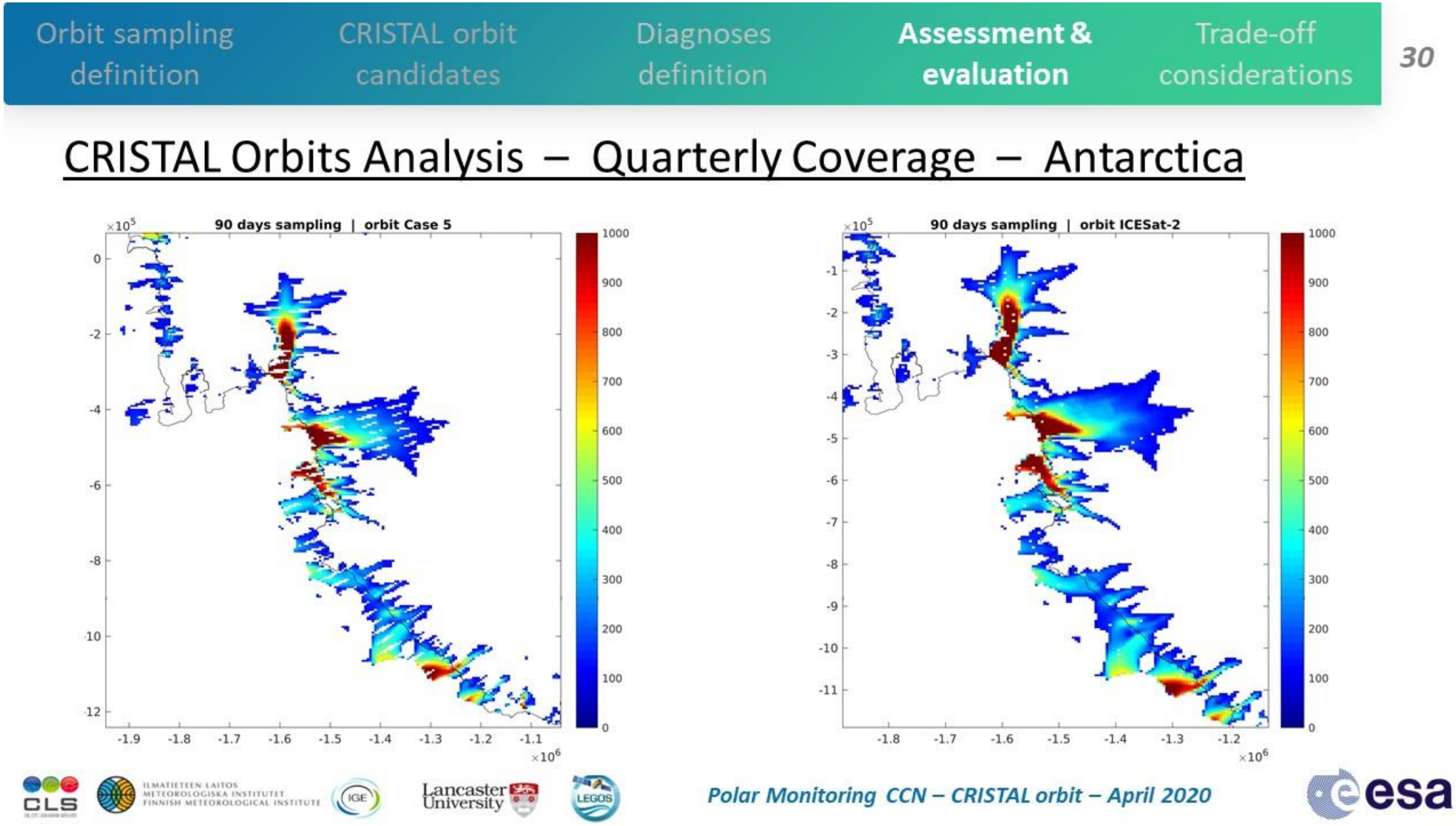
CRISTAL Orbits Analysis – Quarterly Coverage – Antarctica



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

CRISTAL Orbits Analysis – Quarterly Coverage – Antarctica

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

CRISTAL Orbits Analysis – Quarterly Coverage – Antarctica

90 days sampling | orbit Case 5

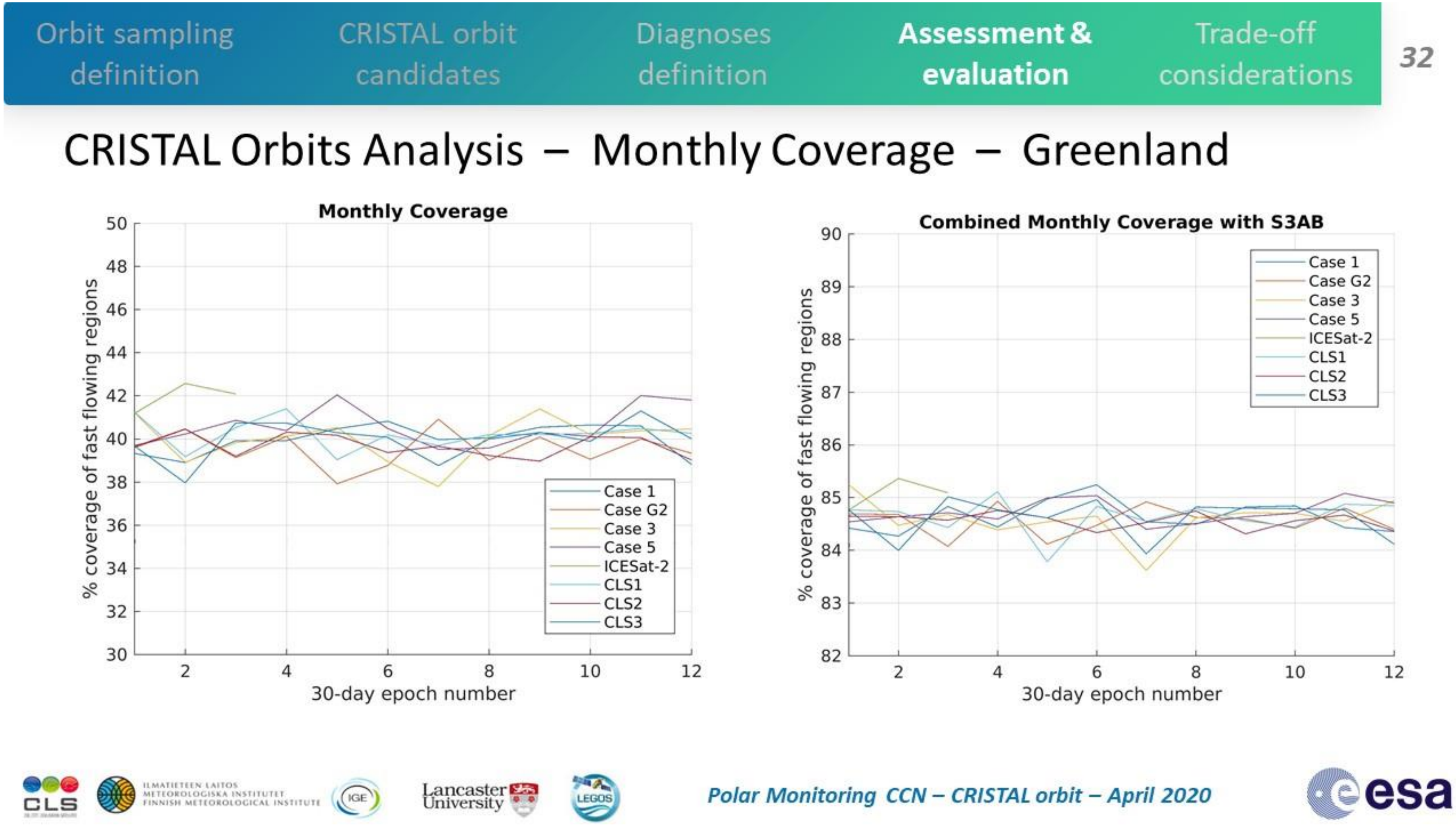
90 days sampling | orbit ICESat-2

Polar Monitoring CCN – CRISTAL orbit – April 2020

Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

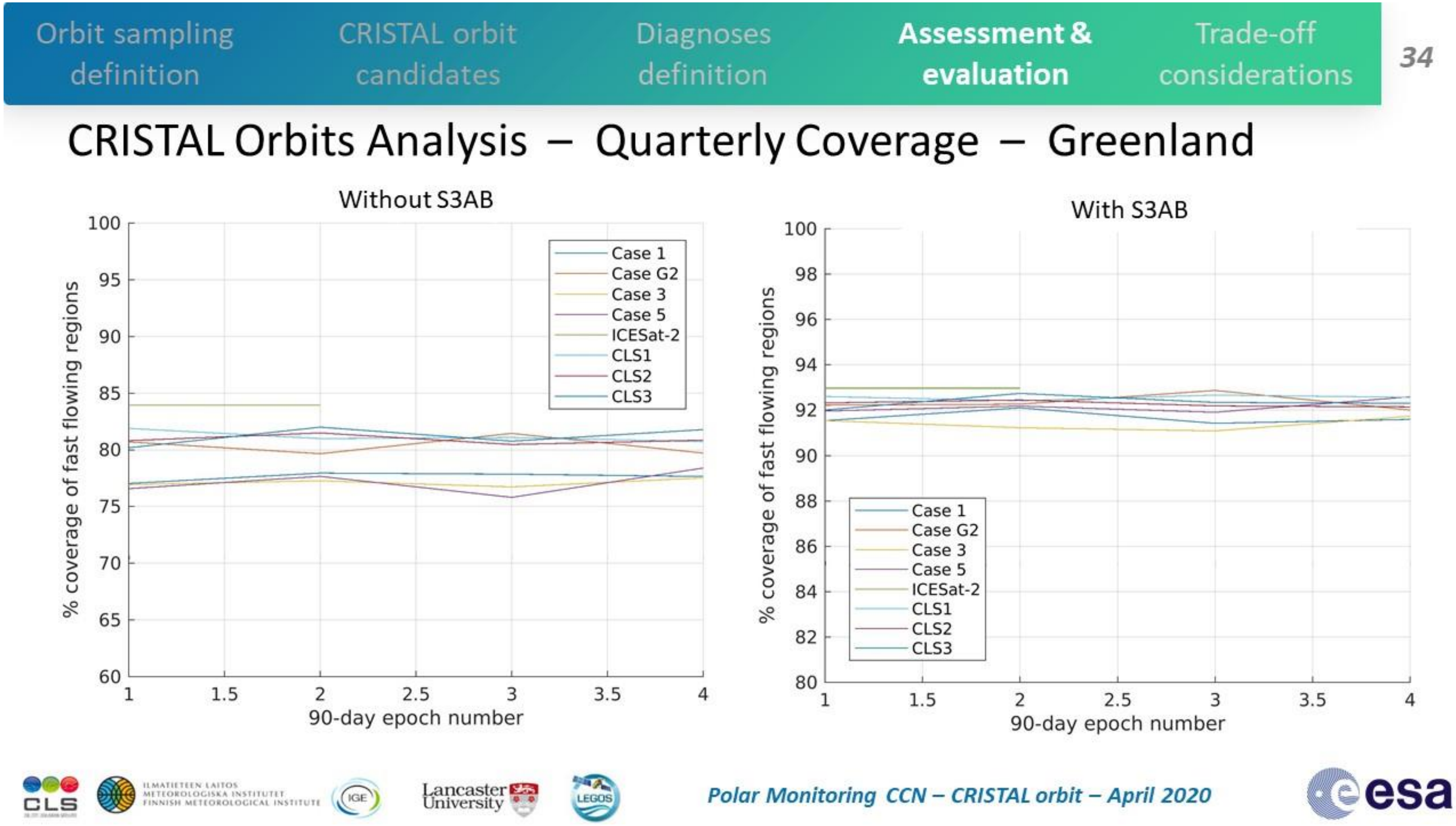
Greenland -- Monthly

Polar Monitoring CCN – CRISTAL orbit – April 2020



CRISTAL Orbits Analysis – Monthly Coverage – Greenland

Greenland -- Quarterly



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

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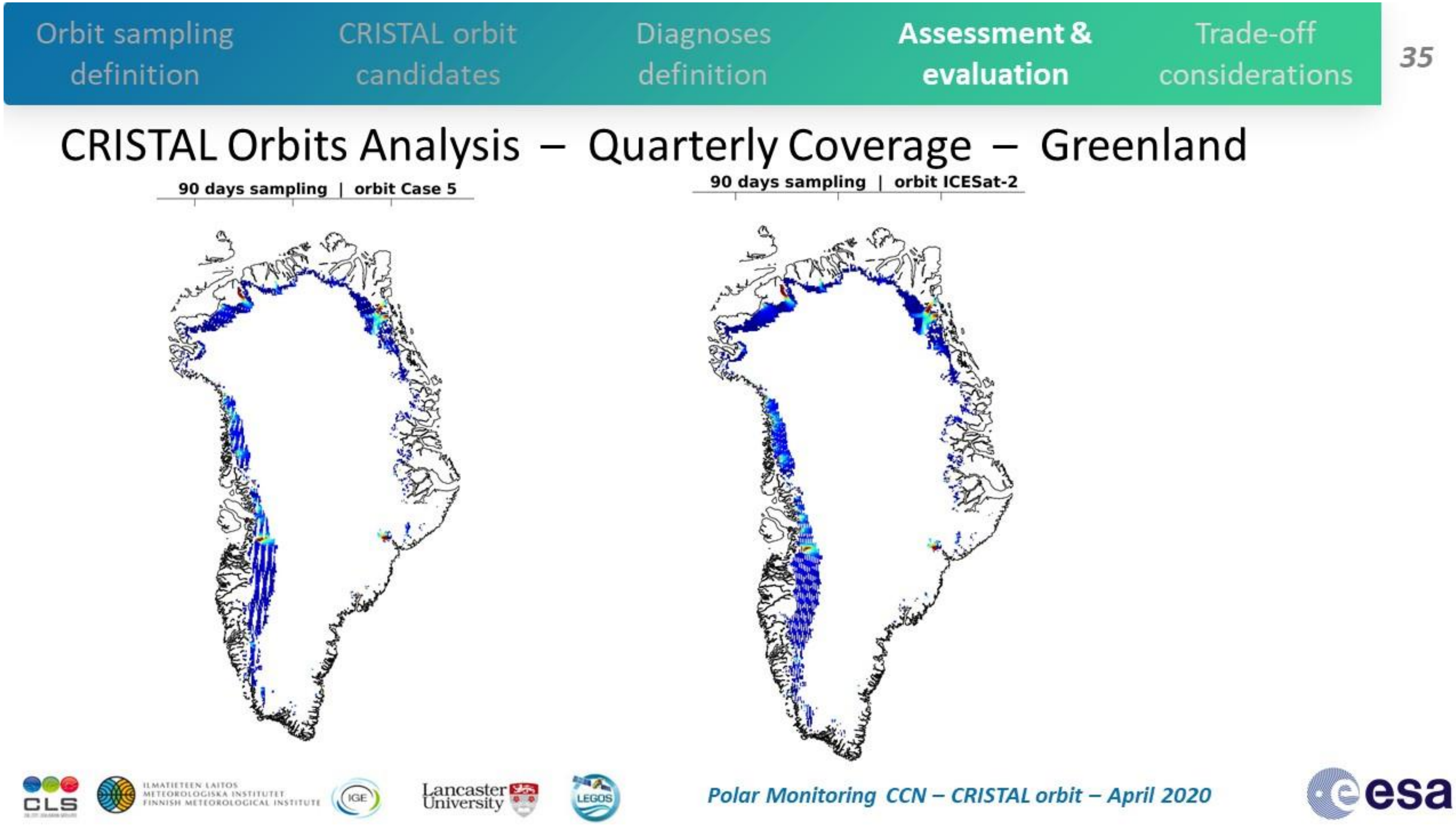
CRISTAL Orbits Analysis – Quarterly Coverage – Greenland

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

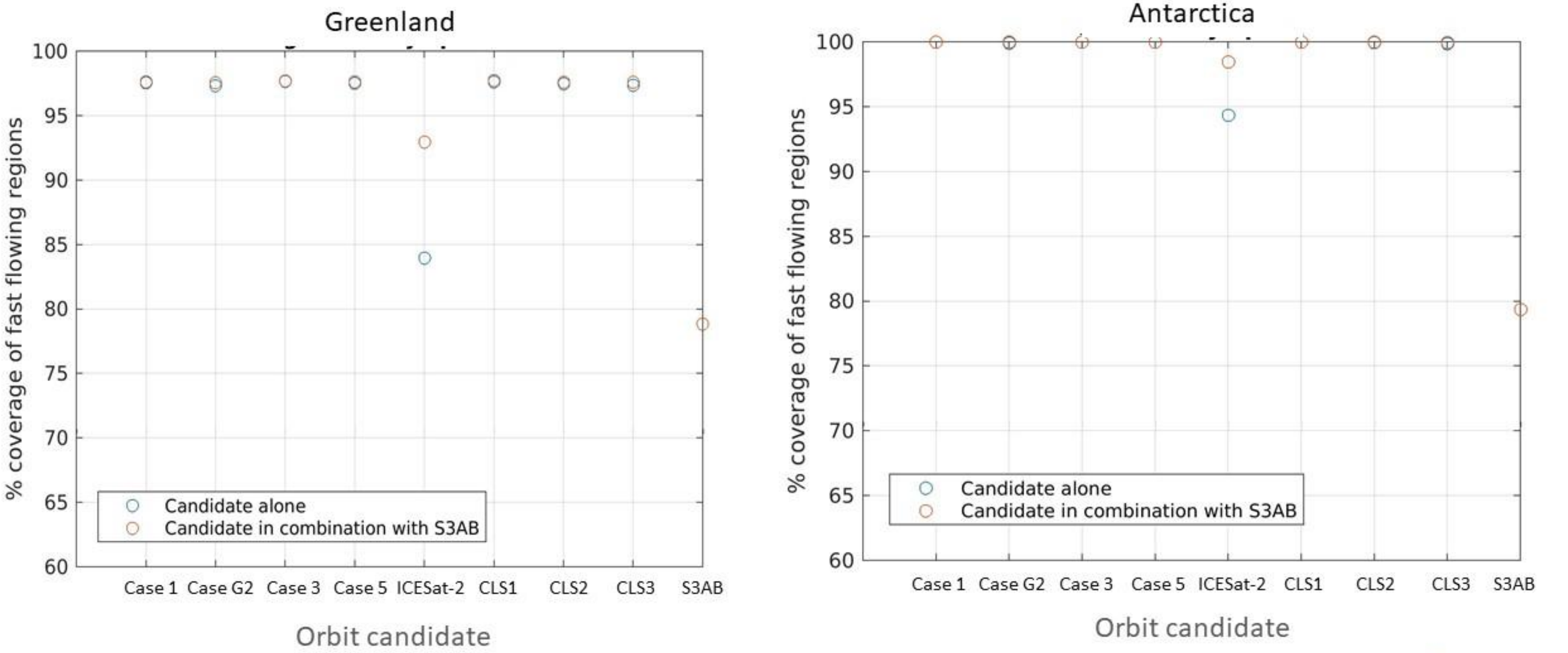
CRISTAL Orbits Analysis – Quarterly Coverage – Greenland

90 days sampling | orbit Case 5

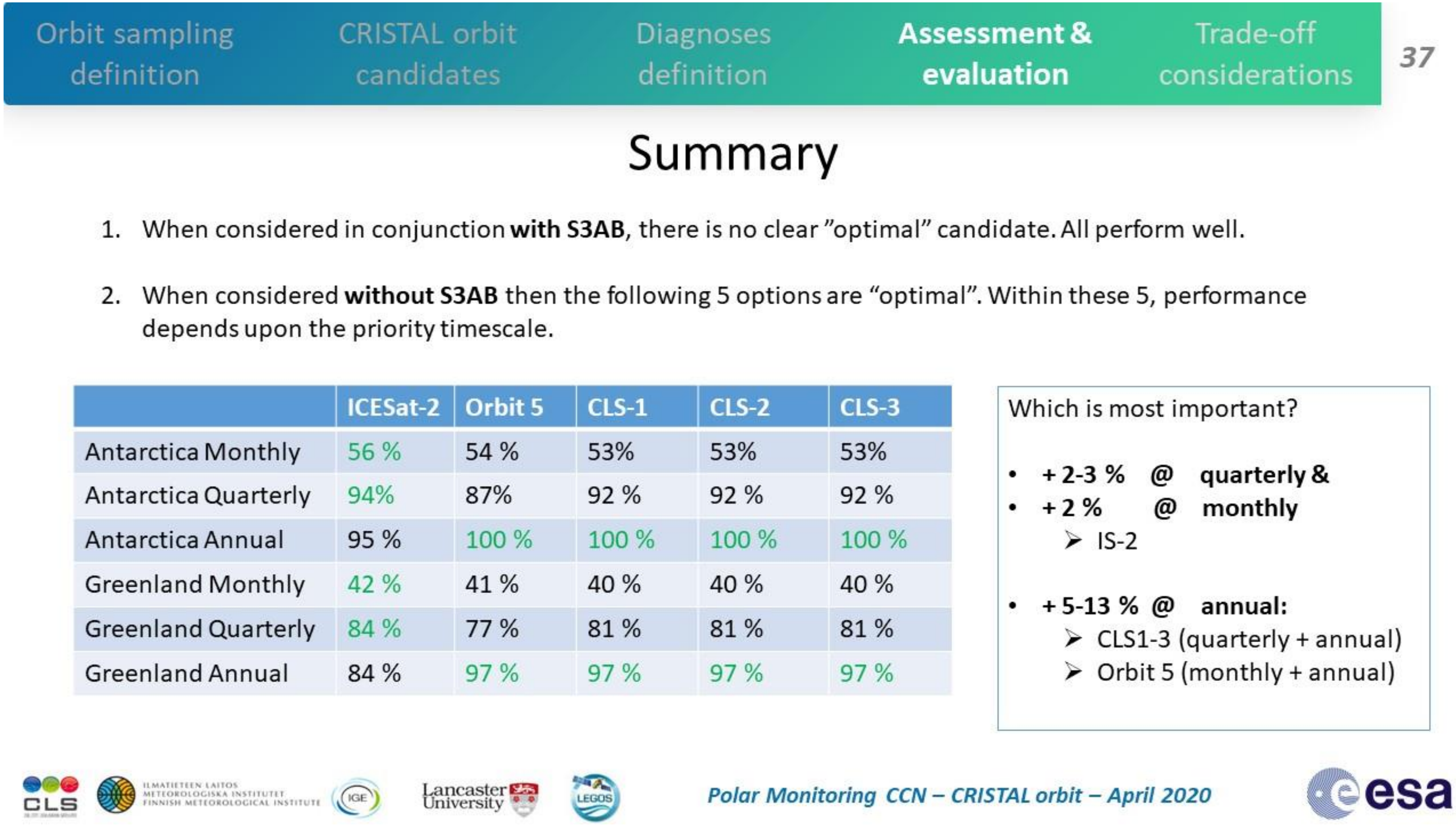
90 days sampling | orbit ICESat-2

Polar Monitoring CCN – CRISTAL orbit – April 2020

CRISTAL Orbits Analysis - fast flow - 365-day coverage



Polar Monitoring CCN – CRISTAL orbit – April 2020



Summary

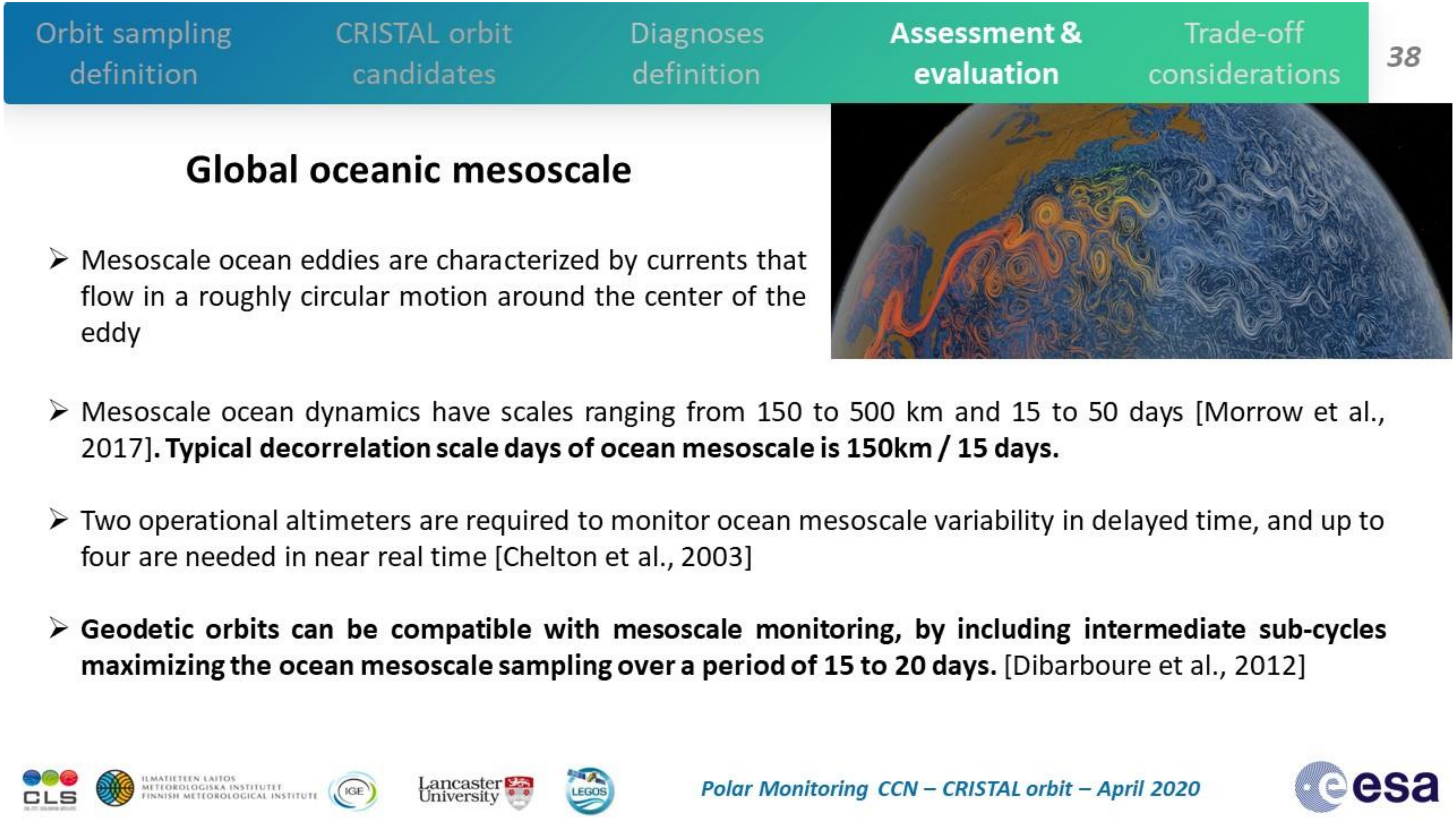
1. When considered in conjunction **with S3AB**, there is no clear ”optimal” candidate. All perform well.
2. When considered **without S3AB** then the following 5 options are “optimal”. Within these 5, performance depends upon the priority timescale.

	ICESat-2	Orbit 5	CLS-1	CLS-2	CLS-3
Antarctica Monthly	56 %	54 %	53%	53%	53%
Antarctica Quarterly	94%	87%	92 %	92 %	92 %
Antarctica Annual	95 %	100 %	100 %	100 %	100 %
Greenland Monthly	42 %	41 %	40 %	40 %	40 %
Greenland Quarterly	84 %	77 %	81 %	81 %	81 %
Greenland Annual	84 %	97 %	97 %	97 %	97 %

Which is most important?

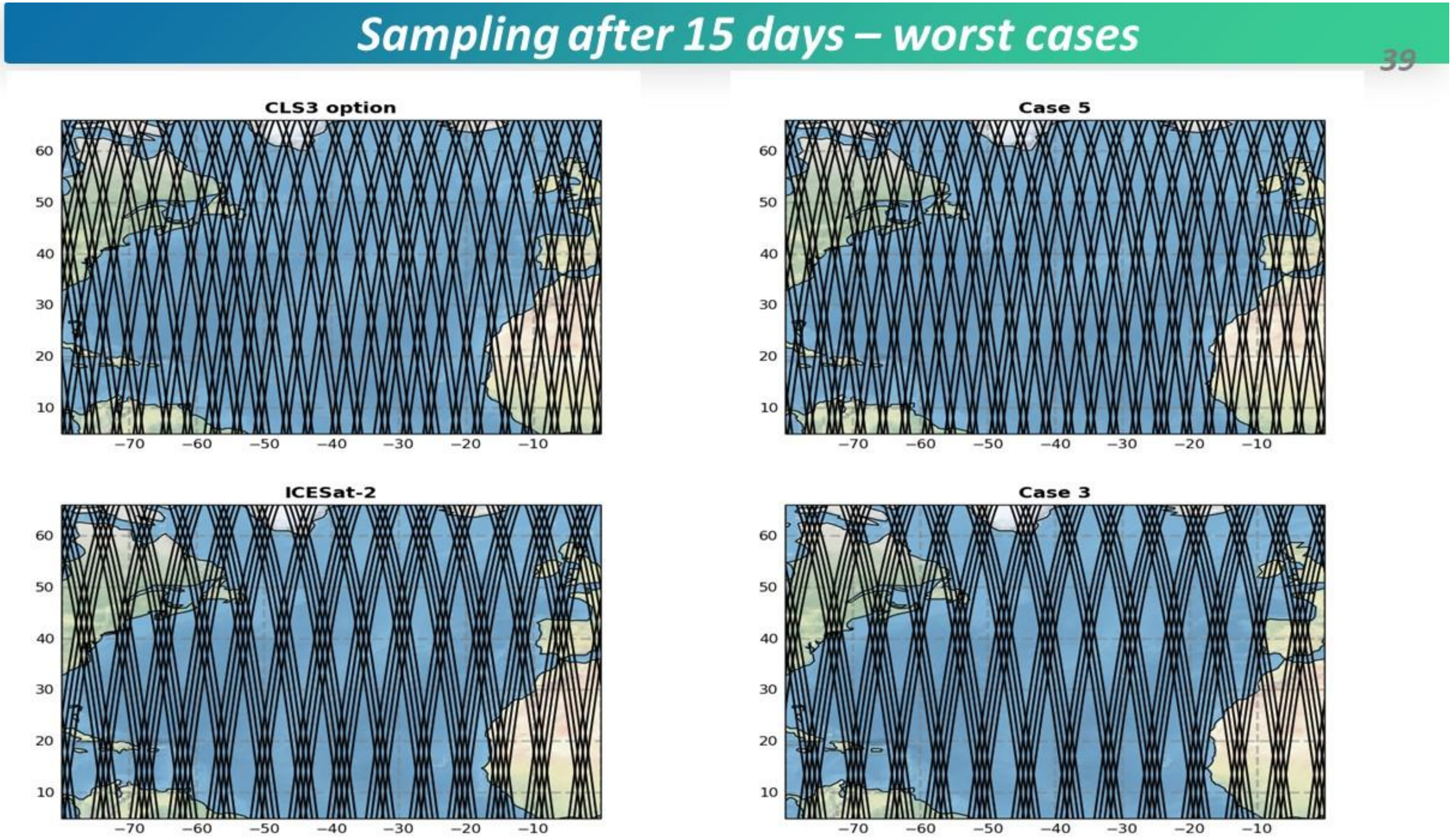
- **+ 2-3 % @ quarterly &**
- **+ 2 % @ monthly**
  - IS-2
- **+ 5-13 % @ annual:**
  - CLS1-3 (quarterly + annual)
  - Orbit 5 (monthly + annual)

Polar Monitoring CCN – CRISTAL orbit – April 2020

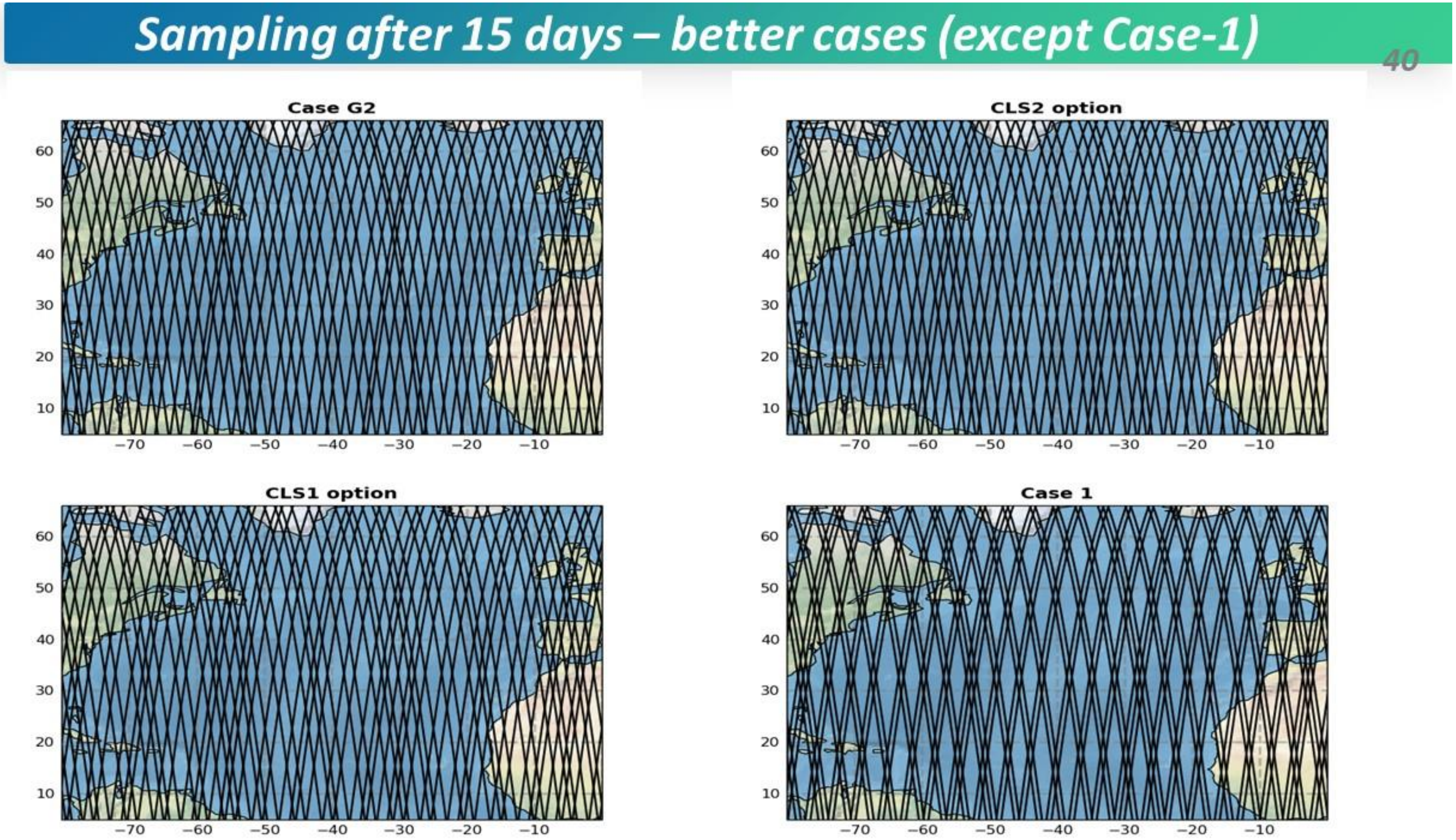


Global oceanic mesoscale

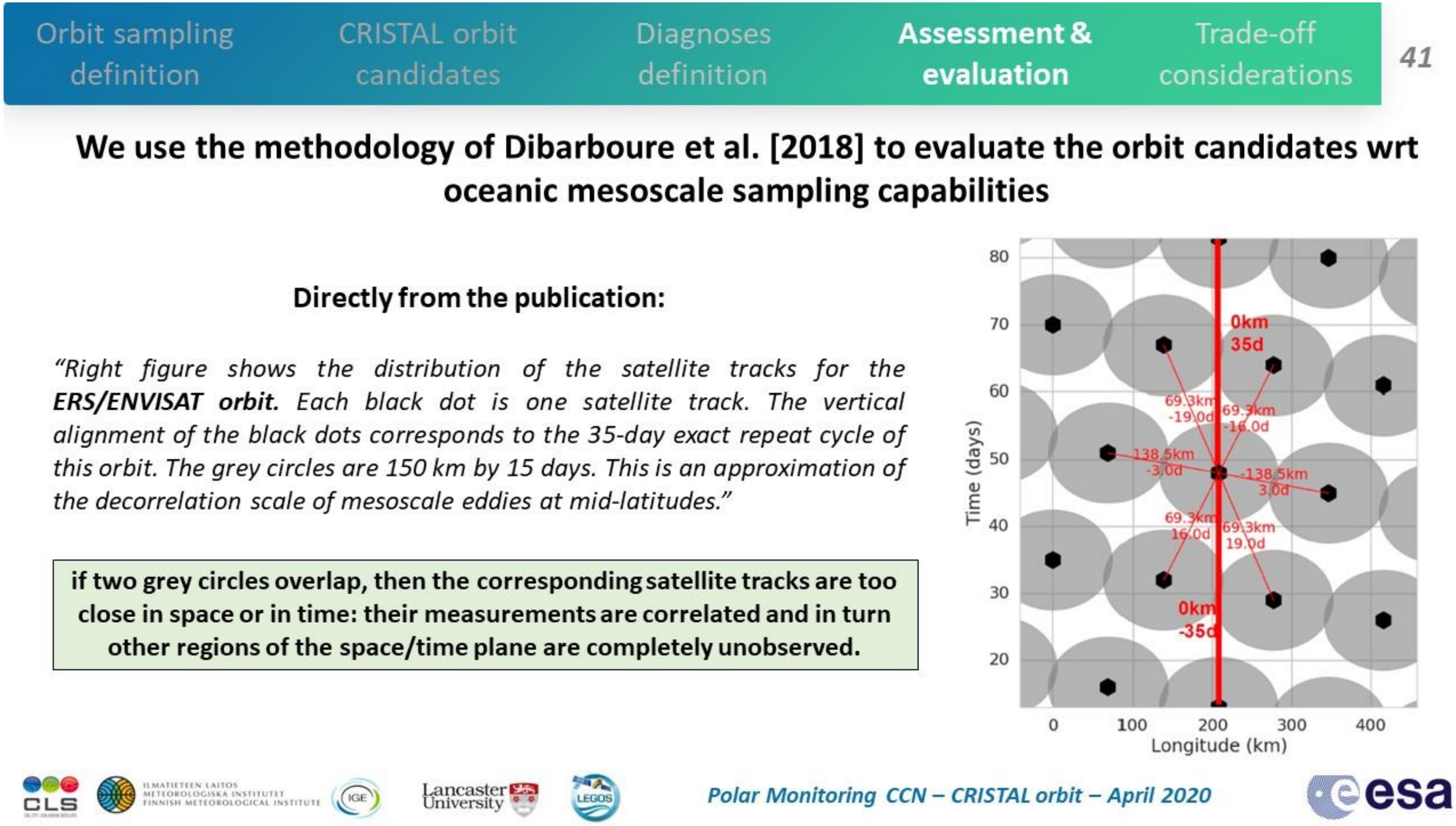
- Mesoscale ocean eddies are characterized by currents that flow in a roughly circular motion around the center of the eddy
- Mesoscale ocean dynamics have scales ranging from 150 to 500 km and 15 to 50 days [Morrow et al., 2017]. **Typical decorrelation scale days of ocean mesoscale is 150km / 15 days.**
- Two operational altimeters are required to monitor ocean mesoscale variability in delayed time, and up to four are needed in near real time [Chelton et al., 2003]
- **Geodetic orbits can be compatible with mesoscale monitoring, by including intermediate sub-cycles maximizing the ocean mesoscale sampling over a period of 15 to 20 days.** [Dibarboure et al., 2012]



Sampling after 15 days – worst cases



Sampling after 15 days – better cases (except Case-1)



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

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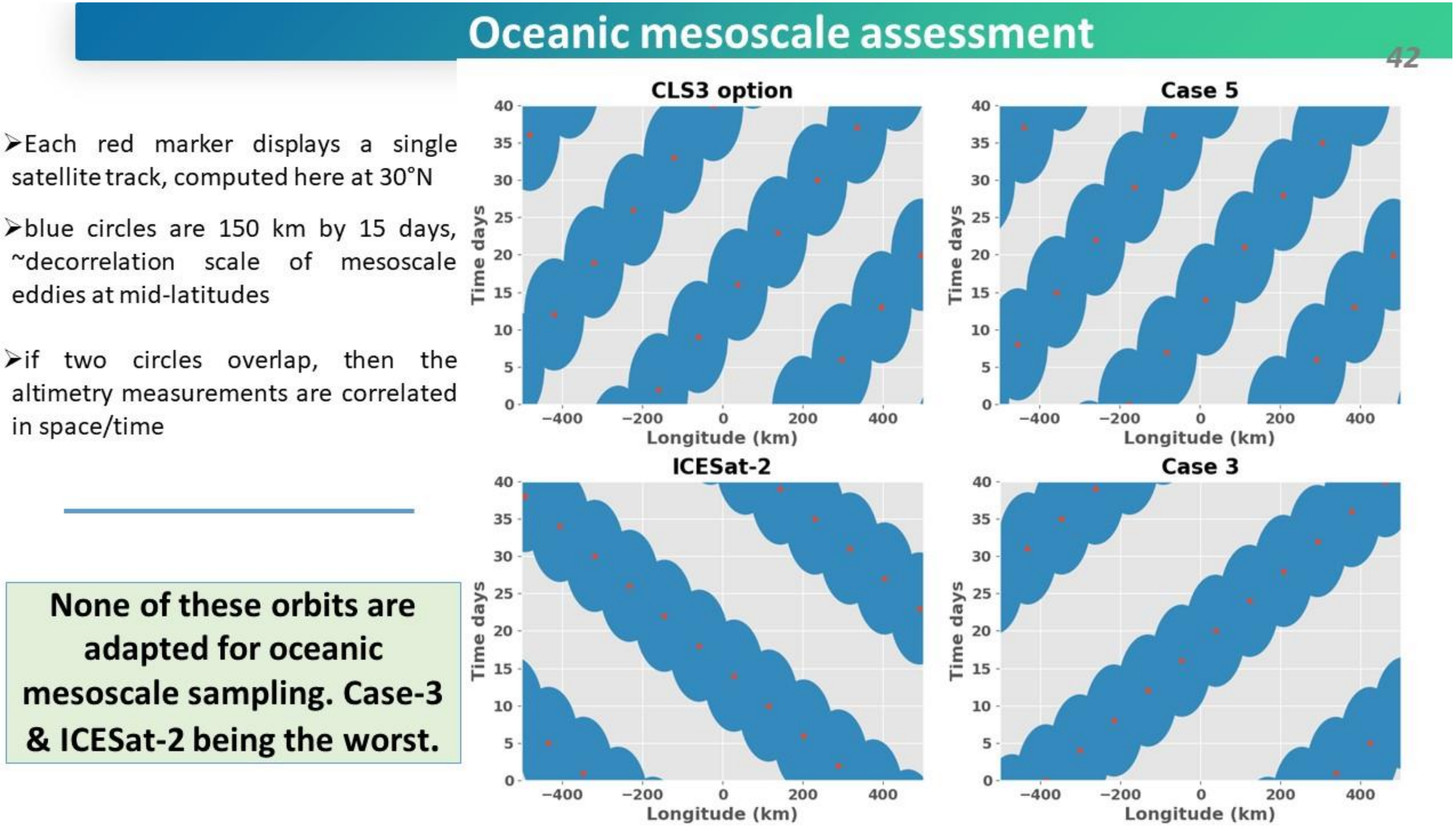
We use the methodology of Dibarboure et al. [2018] to evaluate the orbit candidates wrt oceanic mesoscale sampling capabilities

Directly from the publication:

*“Right figure shows the distribution of the satellite tracks for the **ERS/ENVISAT orbit.** Each black dot is one satellite track. The vertical alignment of the black dots corresponds to the 35-day exact repeat cycle of this orbit. The grey circles are 150 km by 15 days. This is an approximation of the decorrelation scale of mesoscale eddies at mid-latitudes.”*

if two grey circles overlap, then the corresponding satellite tracks are too close in space or in time: their measurements are correlated and in turn other regions of the space/time plane are completely unobserved.

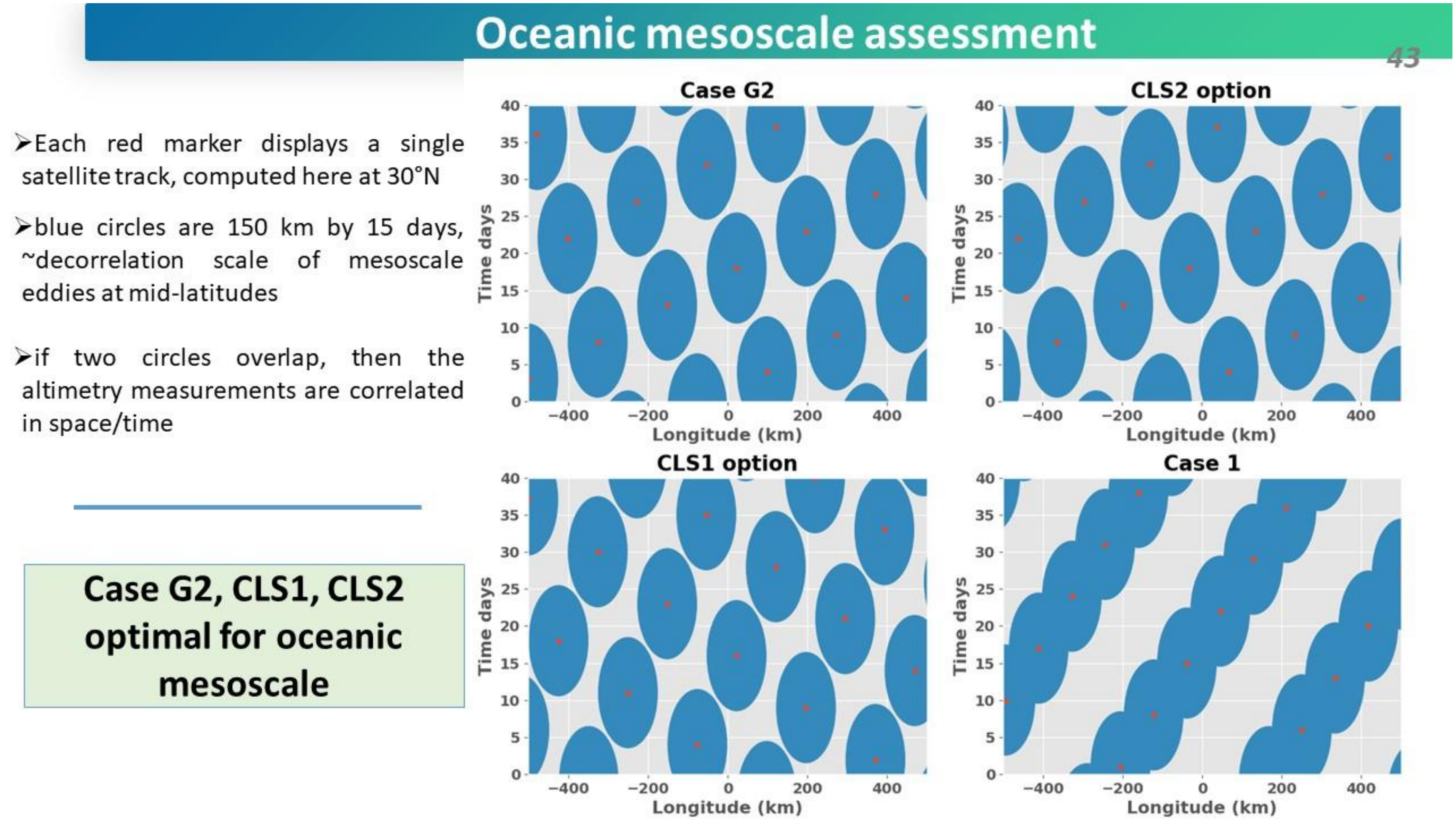
Polar Monitoring CCN – CRISTAL orbit – April 2020



Oceanic mesoscale assessment

- Each red marker displays a single satellite track, computed here at 30°N
- blue circles are 150 km by 15 days, ~decorrelation scale of mesoscale eddies at mid-latitudes
- if two circles overlap, then the altimetry measurements are correlated in space/time

None of these orbits are adapted for oceanic mesoscale sampling. Case-3 & ICESat-2 being the worst.



Oceanic mesoscale assessment

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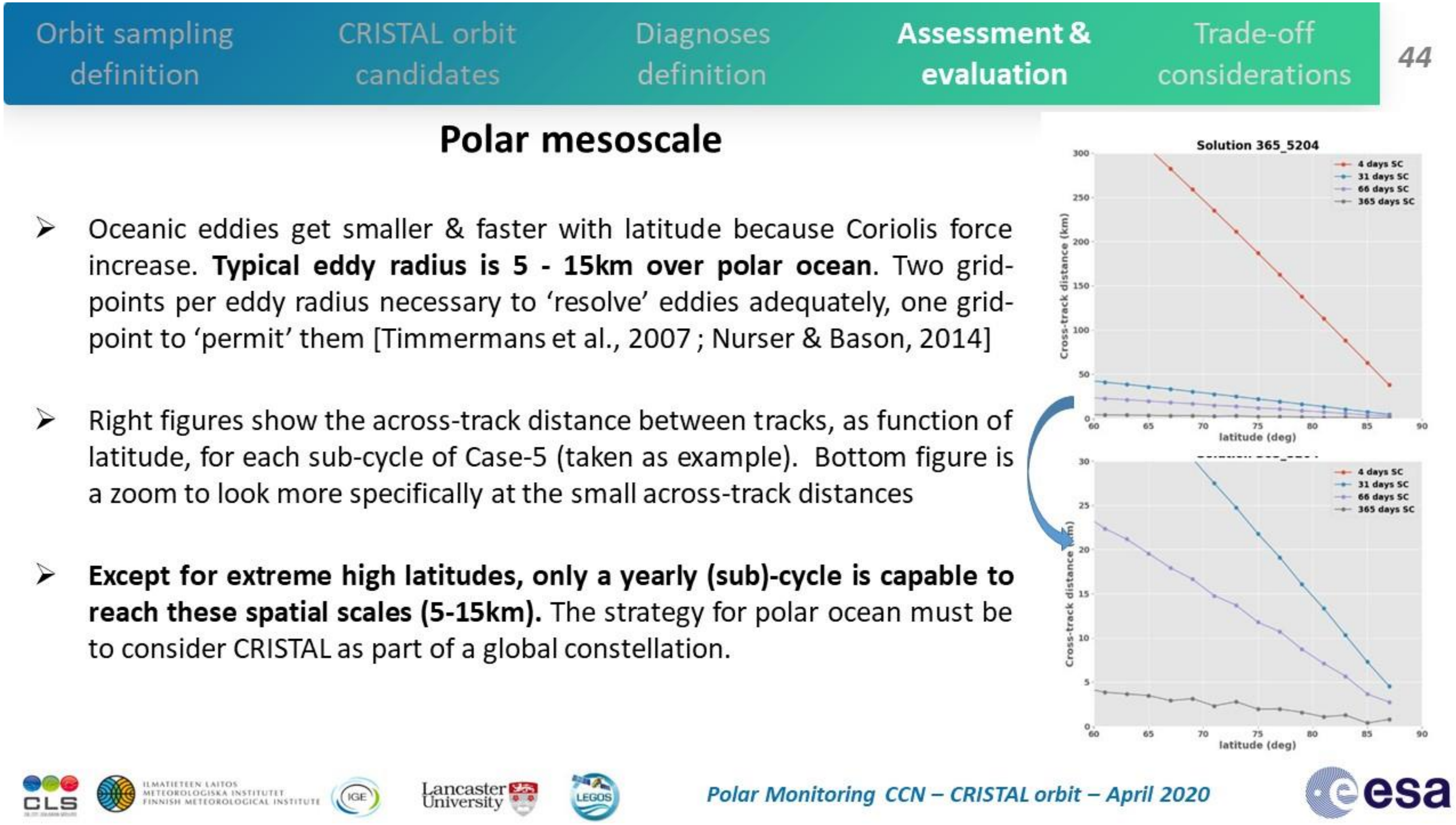
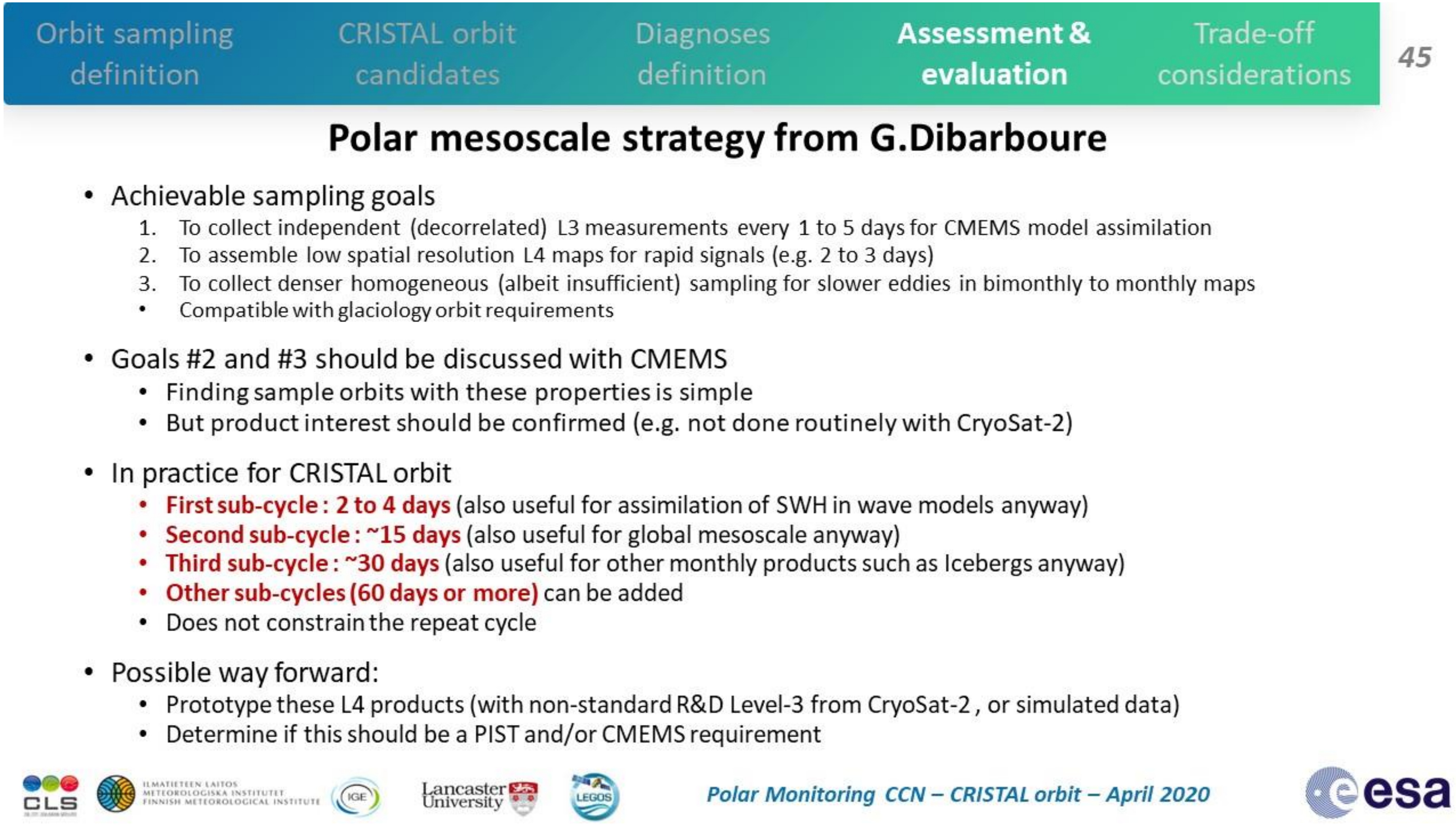
Case G2, CLS1, CLS2 optimal for oceanic mesoscale



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

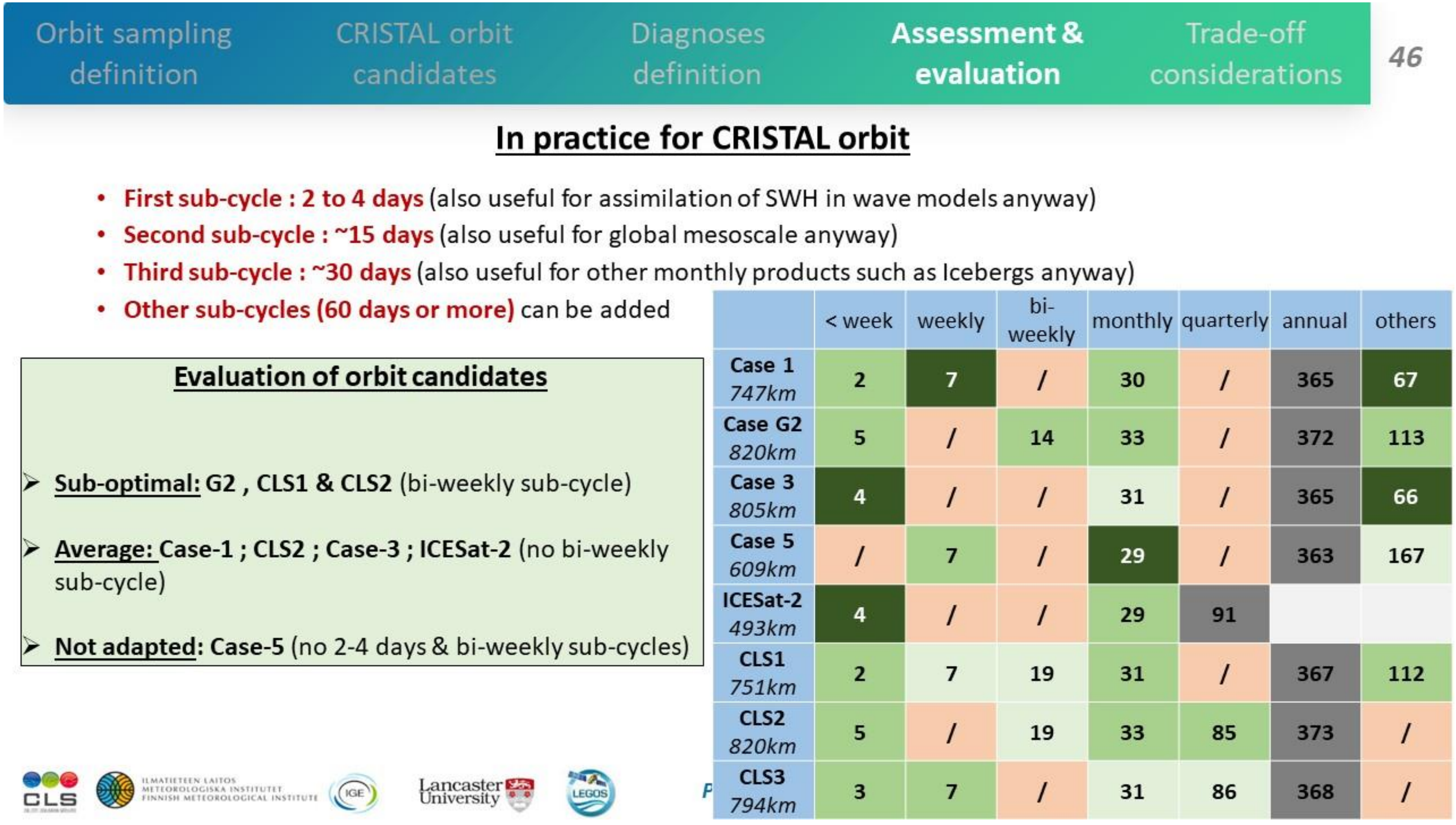
Polar mesoscale

- Oceanic eddies get smaller & faster with latitude because Coriolis force increase. **Typical eddy radius is 5 - 15km over polar ocean**. Two grid-points per eddy radius necessary to 'resolve' eddies adequately, one grid-point to 'permit' them [Timmermans et al., 2007 ; Nurser & Bason, 2014]
- Right figures show the across-track distance between tracks, as function of latitude, for each sub-cycle of Case-5 (taken as example). Bottom figure is a zoom to look more specifically at the small across-track distances
- **Except for extreme high latitudes, only a yearly (sub)-cycle is capable to reach these spatial scales (5-15km).** The strategy for polar ocean must be to consider CRISTAL as part of a global constellation.



Polar mesoscale strategy from G.Dibarboure

- Achievable sampling goals
  1. To collect independent (decorrelated) L3 measurements every 1 to 5 days for CMEMS model assimilation
  2. To assemble low spatial resolution L4 maps for rapid signals (e.g. 2 to 3 days)
  3. To collect denser homogeneous (albeit insufficient) sampling for slower eddies in bimonthly to monthly maps
  - Compatible with glaciology orbit requirements
- Goals #2 and #3 should be discussed with CMEMS
  - Finding sample orbits with these properties is simple
  - But product interest should be confirmed (e.g. not done routinely with CryoSat-2)
- In practice for CRISTAL orbit
  - **First sub-cycle : 2 to 4 days** (also useful for assimilation of SWH in wave models anyway)
  - **Second sub-cycle : ~15 days** (also useful for global mesoscale anyway)
  - **Third sub-cycle : ~30 days** (also useful for other monthly products such as Icebergs anyway)
  - **Other sub-cycles (60 days or more)** can be added
  - Does not constrain the repeat cycle
- Possible way forward:
  - Prototype these L4 products (with non-standard R&D Level-3 from CryoSat-2 , or simulated data)
  - Determine if this should be a PIST and/or CMEMS requirement



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

In practice for CRISTAL orbit

- **First sub-cycle : 2 to 4 days** (also useful for assimilation of SWH in wave models anyway)
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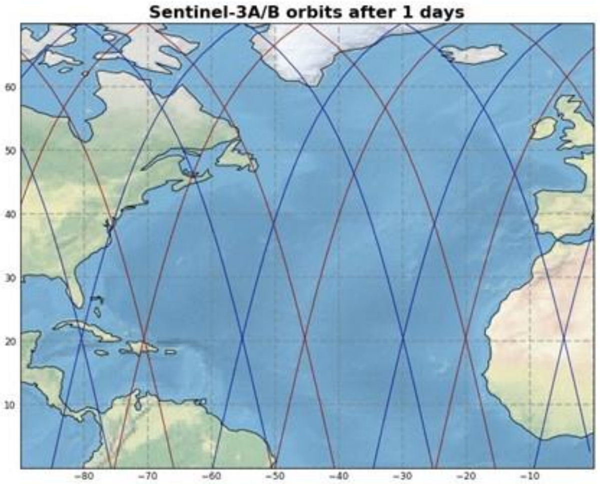
- **Third sub-cycle : ~30 days** (also useful for other monthly products such as Icebergs anyway)
- **Other sub-cycles (60 days or more)** can be added

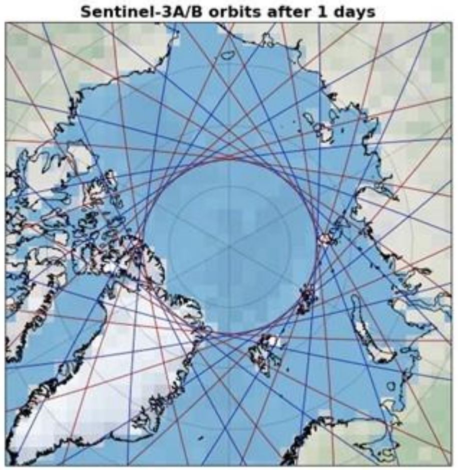
Evaluation of orbit candidates

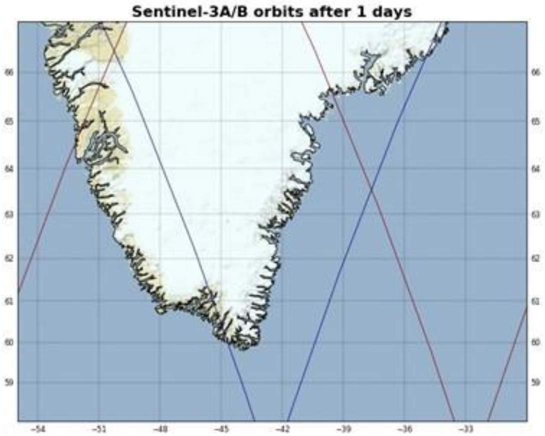
- **Sub-optimal:** **G2 , CLS1 & CLS2** (bi-weekly sub-cycle)
- **Average: Case-1 ; CLS2 ; Case-3 ; ICESat-2** (no bi-weekly sub-cycle)
- **Not adapted: Case-5** (no 2-4 days & bi-weekly sub-cycles)

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1 *747km*	2	7	/	30	/	365	67
Case G2 *820km*	5	/	14	33	/	372	113
Case 3 *805km*	4	/	/	31	/	365	66
Case 5 *609km*	/	7	/	29	/	363	167
ICESat-2 *493km*	4	/	/	29	91		
CLS1 *751km*	2	7	19	31	/	367	112
CLS2 *820km*	5	/	19	33	85	373	/
CLS3 *794km*	3	7	/	31	86	368	/

Complementarity with Sentinel-3X + Sentinel-3Y

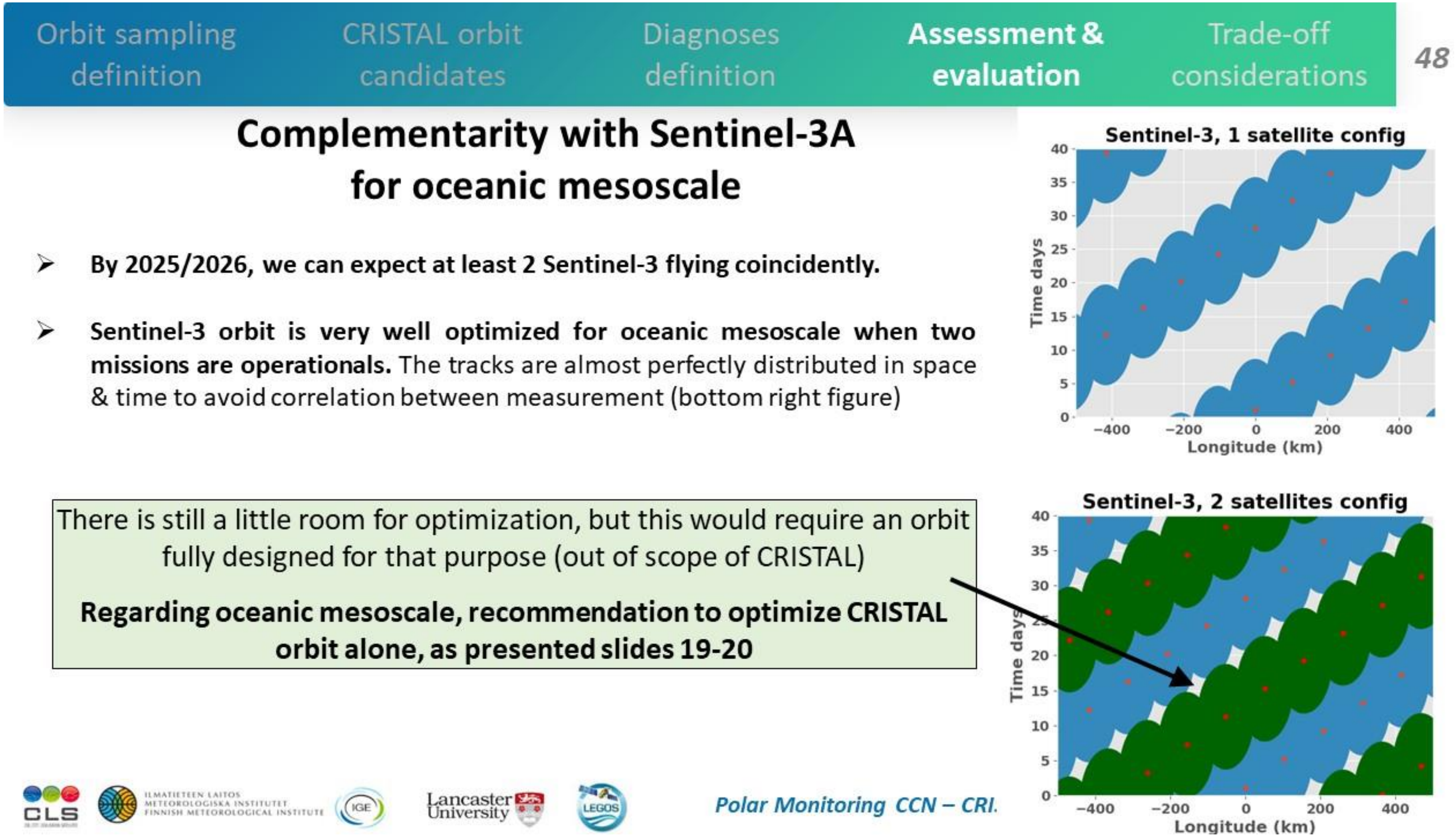

Sentinel-3A/B orbits after 1 days


Sentinel-3A/B orbits after 1 days


Sentinel-3A/B orbits after 1 days

Sentinel-3A has an inclination of 98.65° (max. latitude = **81.35°).** The orbit reference altitude is 814.5 km (orbit similar to ERS/Envisat to continue the time series).

Sentinel-3B's orbit is identical to Sentinel-3A's orbit but flies +/-140° out of phase with Sentinel-3A



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

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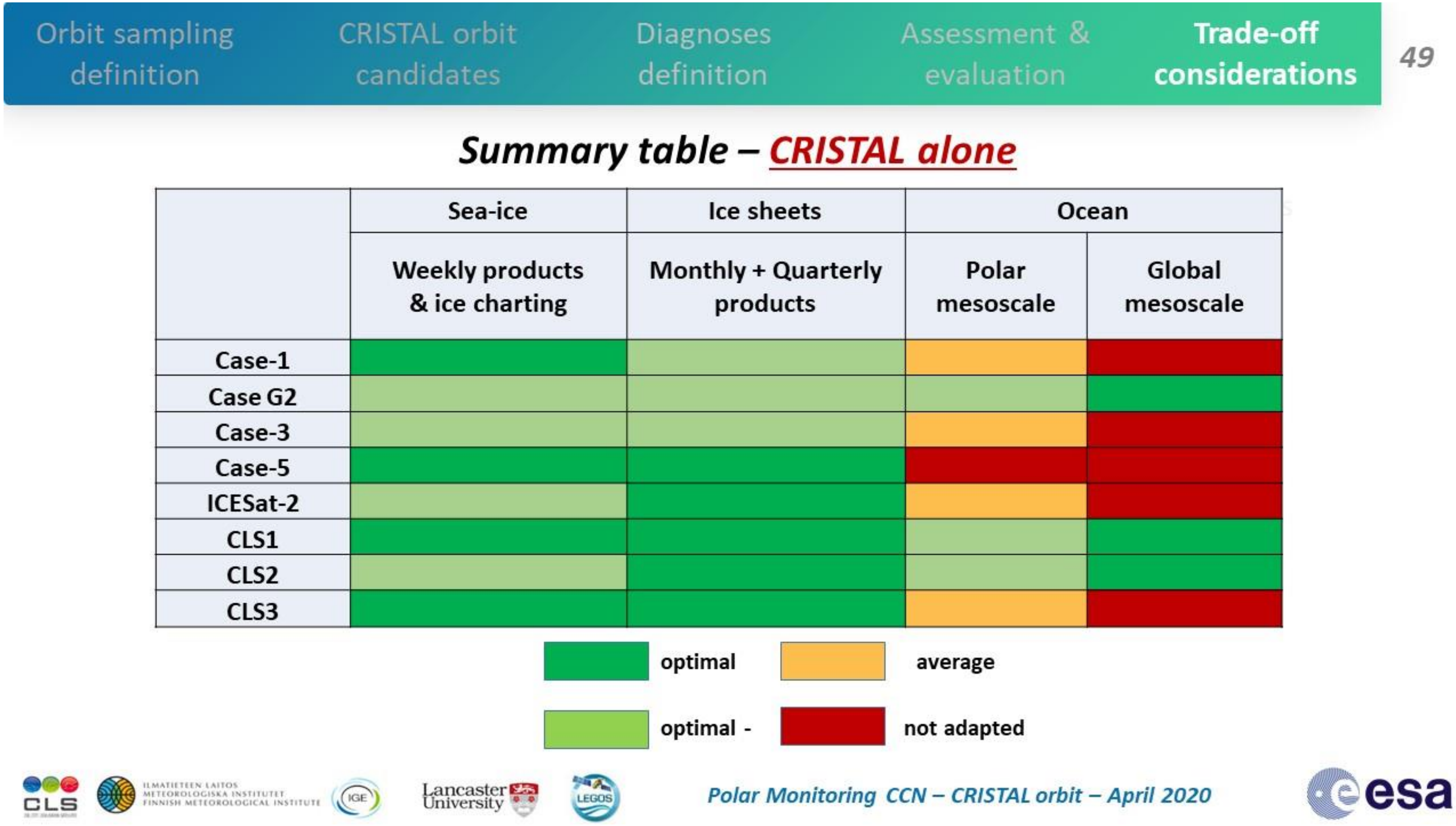
Complementarity with Sentinel-3A for oceanic mesoscale

- **By 2025/2026, we can expect at least 2 Sentinel-3 flying coincidently.**
- **Sentinel-3 orbit is very well optimized for oceanic mesoscale when two missions are operationals.** The tracks are almost perfectly distributed in space & time to avoid correlation between measurement (bottom right figure)

There is still a little room for optimization, but this would require an orbit fully designed for that purpose (out of scope of CRISTAL)

Regarding oceanic mesoscale, recommendation to optimize CRISTAL orbit alone, as presented slides 19-20

Polar Monitoring CCN – CRI.



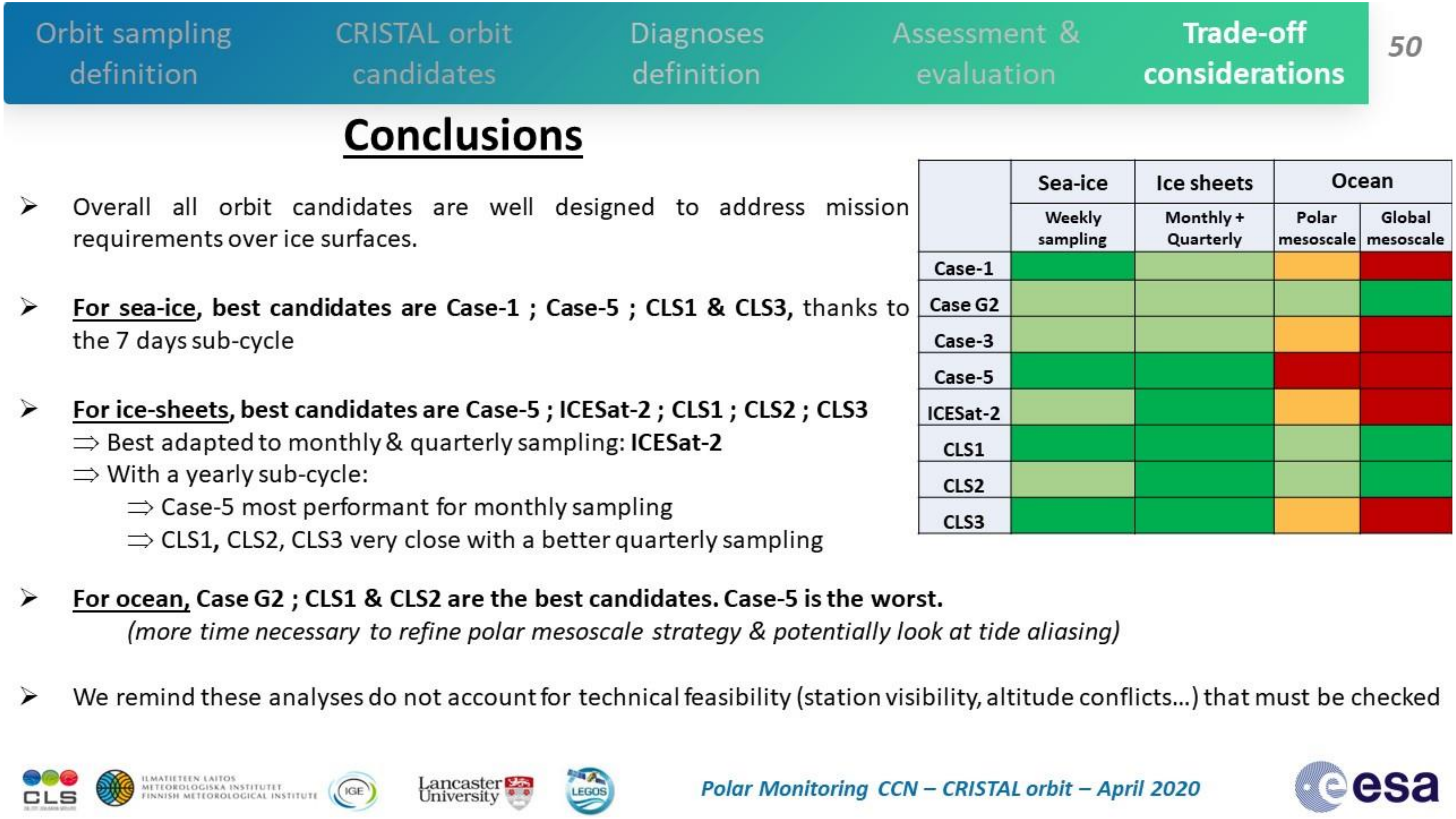
Summary table – CRISTAL alone

	Sea-ice	Ice sheets	Ocean	
	Weekly products & ice charting	Monthly + Quarterly products	Polar mesoscale	Global mesoscale
Case-1	🟩	🟢	🟧	🟥
Case G2	🟢	🟢	🟢	🟩
Case-3	🟢	🟢	🟧	🟥
Case-5	🟩	🟩	🟥	🟥
ICESat-2	🟢	🟩	🟧	🟥
CLS1	🟩	🟩	🟢	🟩
CLS2	🟢	🟩	🟢	🟩
CLS3	🟩	🟩	🟧	🟥

🟩 optimal 🟧 average

🟢 optimal - 🟥 not adapted

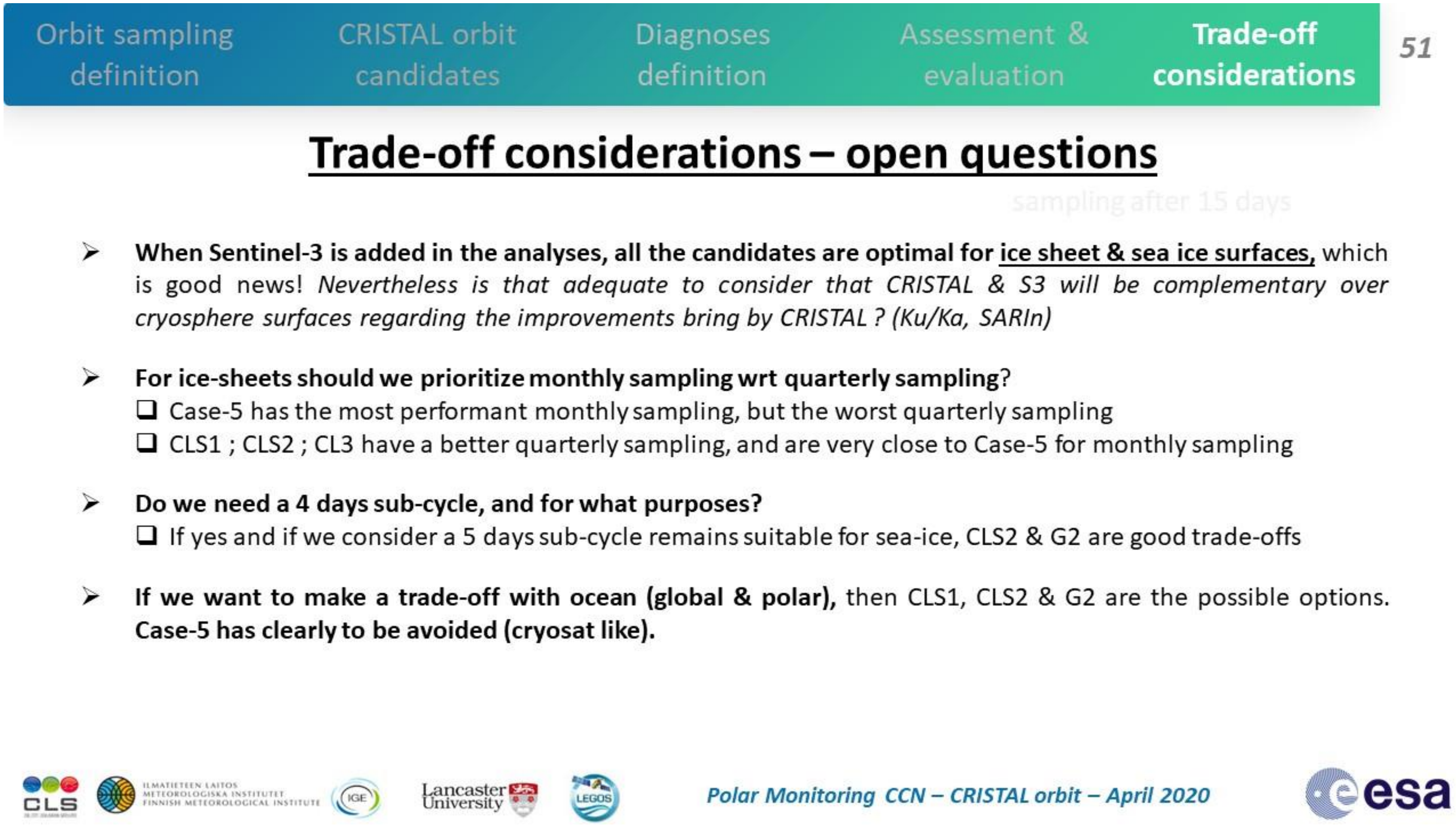
Polar Monitoring CCN – CRISTAL orbit – April 2020



Conclusions

	Sea-ice	Ice sheets	Ocean	
	Weekly sampling	Monthly + Quarterly	Polar mesoscale	Global mesoscale
Case-1	🟩	▩	🟧	🟥
Case G2	▩	▩	▩	🟩
Case-3	▩	▩	🟧	🟥
Case-5	🟩	🟩	🟥	🟥
ICESat-2	▩	🟩	🟧	🟥
CLS1	🟩	🟩	▩	🟩
CLS2	▩	🟩	▩	🟩
CLS3	🟩	🟩	🟧	🟥

- Overall all orbit candidates are well designed to address mission requirements over ice surfaces.
- **<u>For sea-ice</u>, best candidates are Case-1 ; Case-5 ; CLS1 & CLS3,** thanks to the 7 days sub-cycle
- **<u>For ice-sheets</u>, best candidates are Case-5 ; ICESat-2 ; CLS1 ; CLS2 ; CLS3**
  - ⇒ Best adapted to monthly & quarterly sampling: **ICESat-2**
  - ⇒ With a yearly sub-cycle:
    - ⇒ Case-5 most performant for monthly sampling
    - ⇒ CLS1, CLS2, CLS3 very close with a better quarterly sampling
- **<u>For ocean,</u> Case G2 ; CLS1 & CLS2 are the best candidates. Case-5 is the worst.**
  (more time necessary to refine polar mesoscale strategy & potentially look at tide aliasing)
- We remind these analyses do not account for technical feasibility (station visibility, altitude conflicts…) that must be checked



Trade-off considerations – open questions

sampling after 15 days

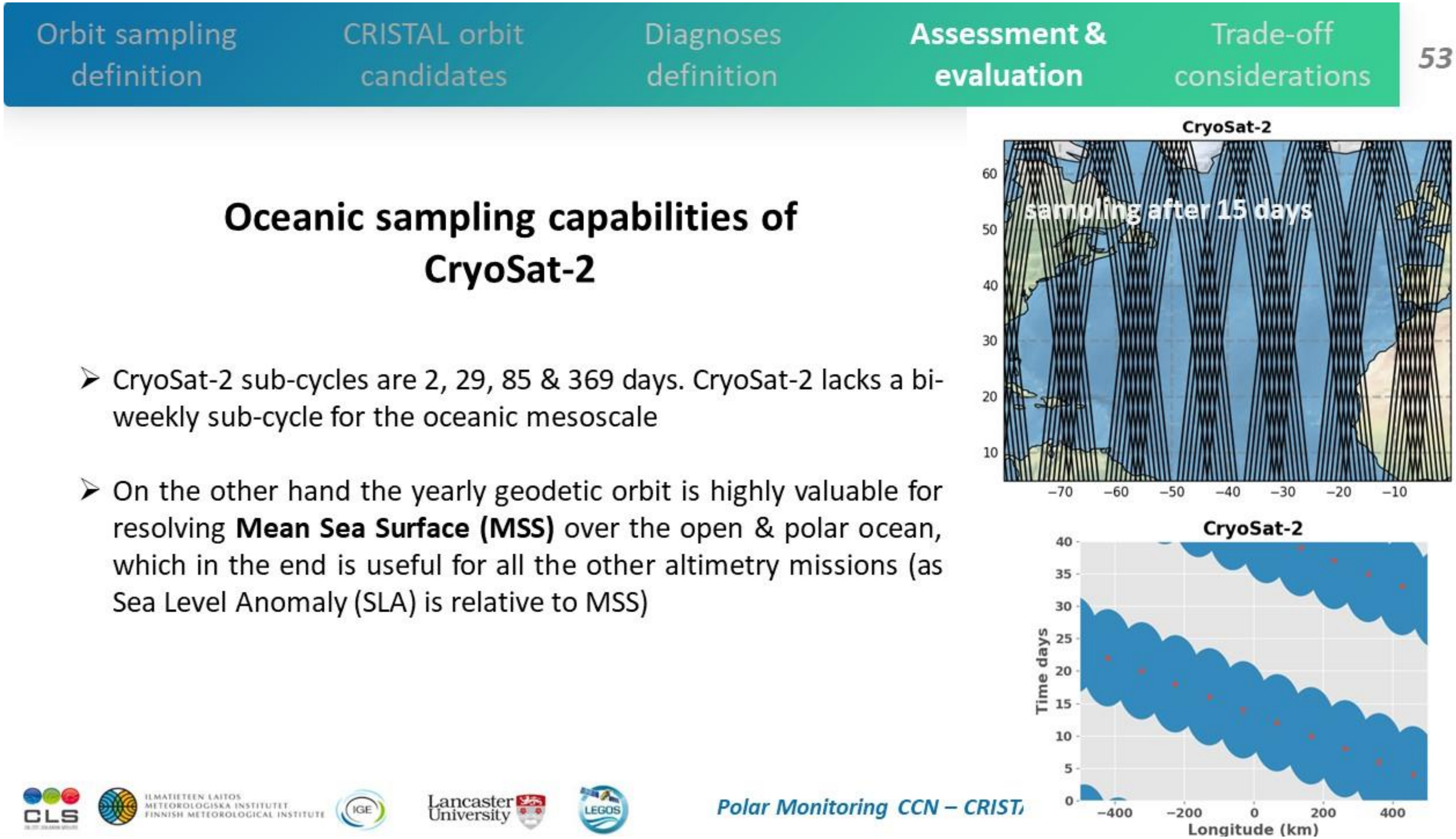
- **When Sentinel-3 is added in the analyses, all the candidates are optimal for ice sheet & sea ice surfaces,** which is good news! *Nevertheless is that adequate to consider that CRISTAL & S3 will be complementary over cryosphere surfaces regarding the improvements bring by CRISTAL ? (Ku/Ka, SARIn)*

- **For ice-sheets should we prioritize monthly sampling wrt quarterly sampling**?
  - ☐ Case-5 has the most performant monthly sampling, but the worst quarterly sampling
  - ☐ CLS1 ; CLS2 ; CL3 have a better quarterly sampling, and are very close to Case-5 for monthly sampling

- **Do we need a 4 days sub-cycle, and for what purposes?**
  - ☐ If yes and if we consider a 5 days sub-cycle remains suitable for sea-ice, CLS2 & G2 are good trade-offs

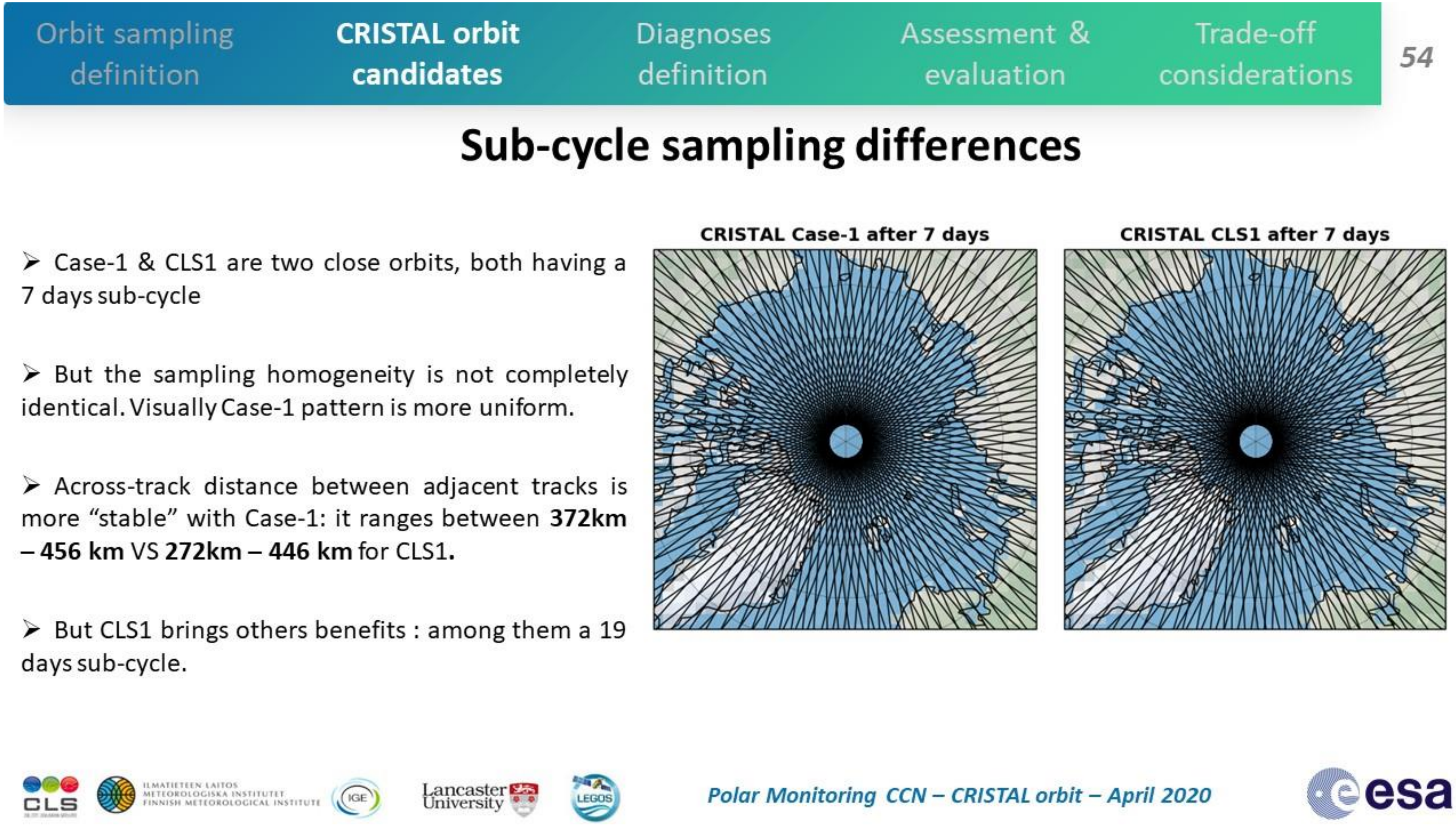
- **If we want to make a trade-off with ocean (global & polar),** then CLS1, CLS2 & G2 are the possible options. **Case-5 has clearly to be avoided (cryosat like).**

BACK UP



Oceanic sampling capabilities of CryoSat-2

- CryoSat-2 sub-cycles are 2, 29, 85 & 369 days. CryoSat-2 lacks a bi-weekly sub-cycle for the oceanic mesoscale
- On the other hand the yearly geodetic orbit is highly valuable for resolving **Mean Sea Surface (MSS)** over the open & polar ocean, which in the end is useful for all the other altimetry missions (as Sea Level Anomaly (SLA) is relative to MSS)



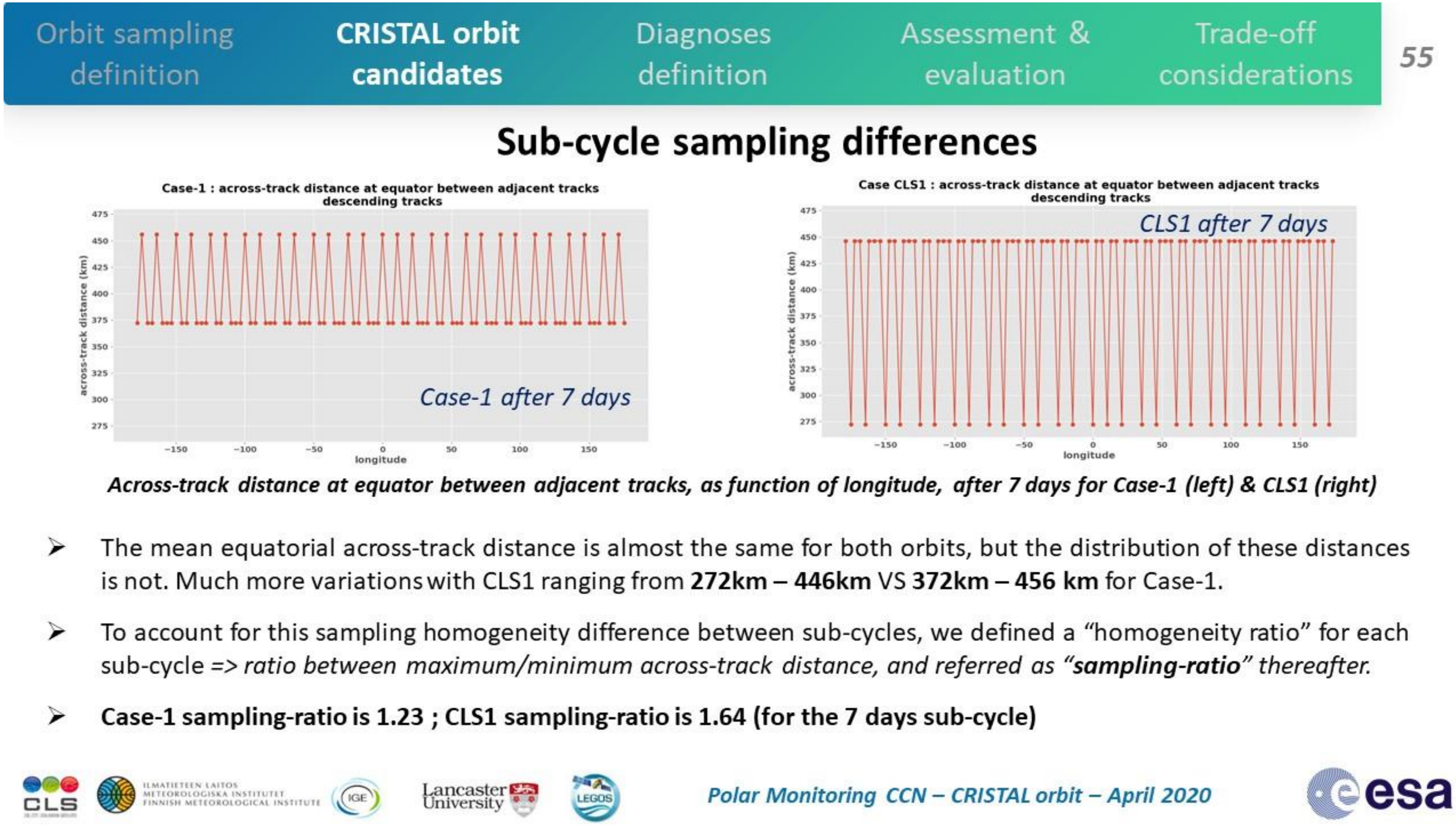
Sub-cycle sampling differences

- ➢ Case-1 & CLS1 are two close orbits, both having a 7 days sub-cycle

- ➢ But the sampling homogeneity is not completely identical. Visually Case-1 pattern is more uniform.

- ➢ Across-track distance between adjacent tracks is more “stable” with Case-1: it ranges between **372km – 456 km** VS **272km – 446 km** for CLS1**.**

- ➢ But CLS1 brings others benefits : among them a 19 days sub-cycle.



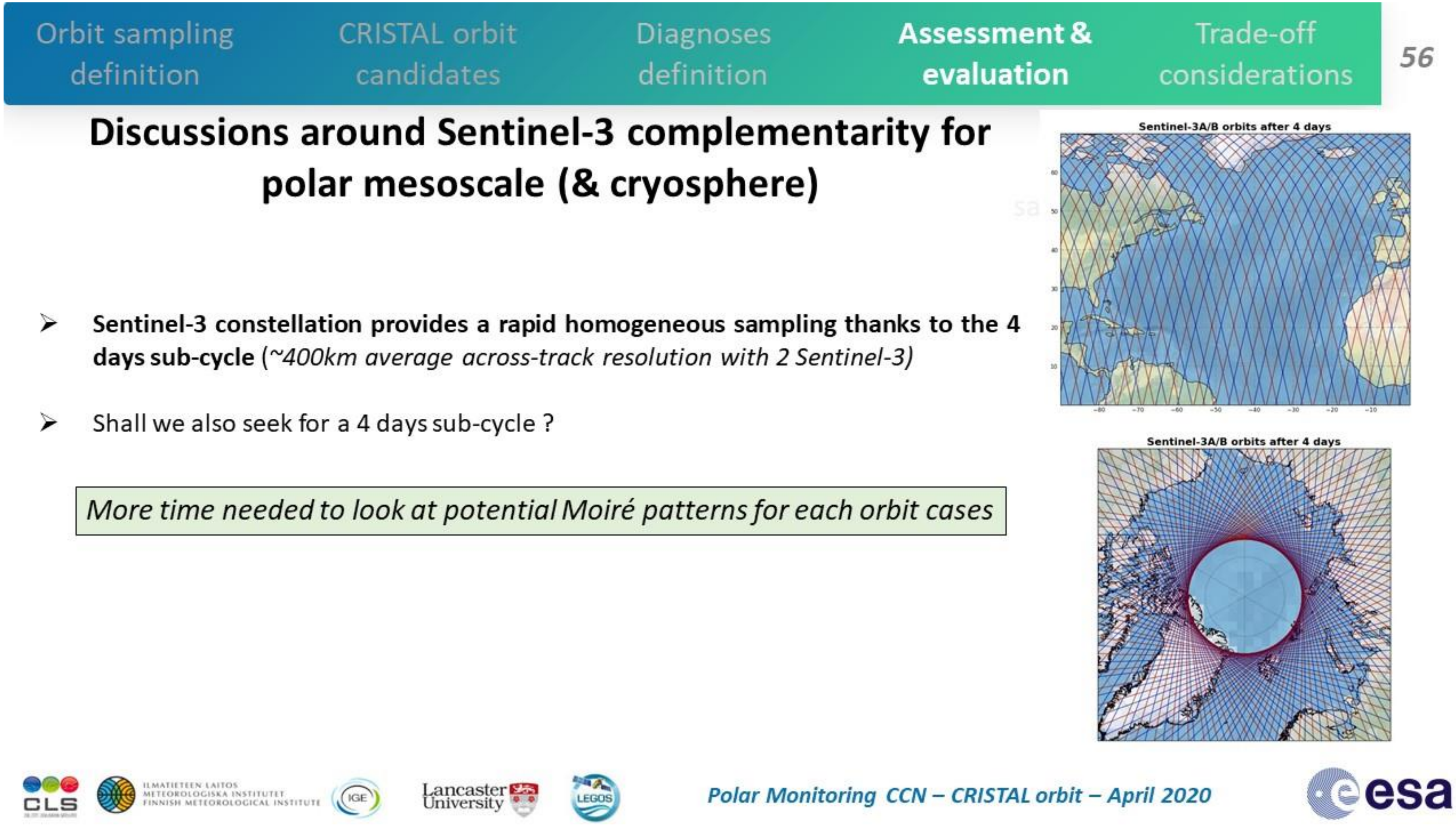
Orbit sampling definition | **CRISTAL orbit candidates** | Diagnoses definition | Assessment & evaluation | Trade-off considerations

Sub-cycle sampling differences

Across-track distance at equator between adjacent tracks, as function of longitude, after 7 days for Case-1 (left) & CLS1 (right)

- The mean equatorial across-track distance is almost the same for both orbits, but the distribution of these distances is not. Much more variations with CLS1 ranging from **272km – 446km** VS **372km – 456 km** for Case-1.
- To account for this sampling homogeneity difference between sub-cycles, we defined a “homogeneity ratio” for each sub-cycle => *ratio between maximum/minimum across-track distance, and referred as “**sampling-ratio**” thereafter.*
- **Case-1 sampling-ratio is 1.23 ; CLS1 sampling-ratio is 1.64 (for the 7 days sub-cycle)**

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | Diagnoses definition | **Assessment & evaluation** | Trade-off considerations

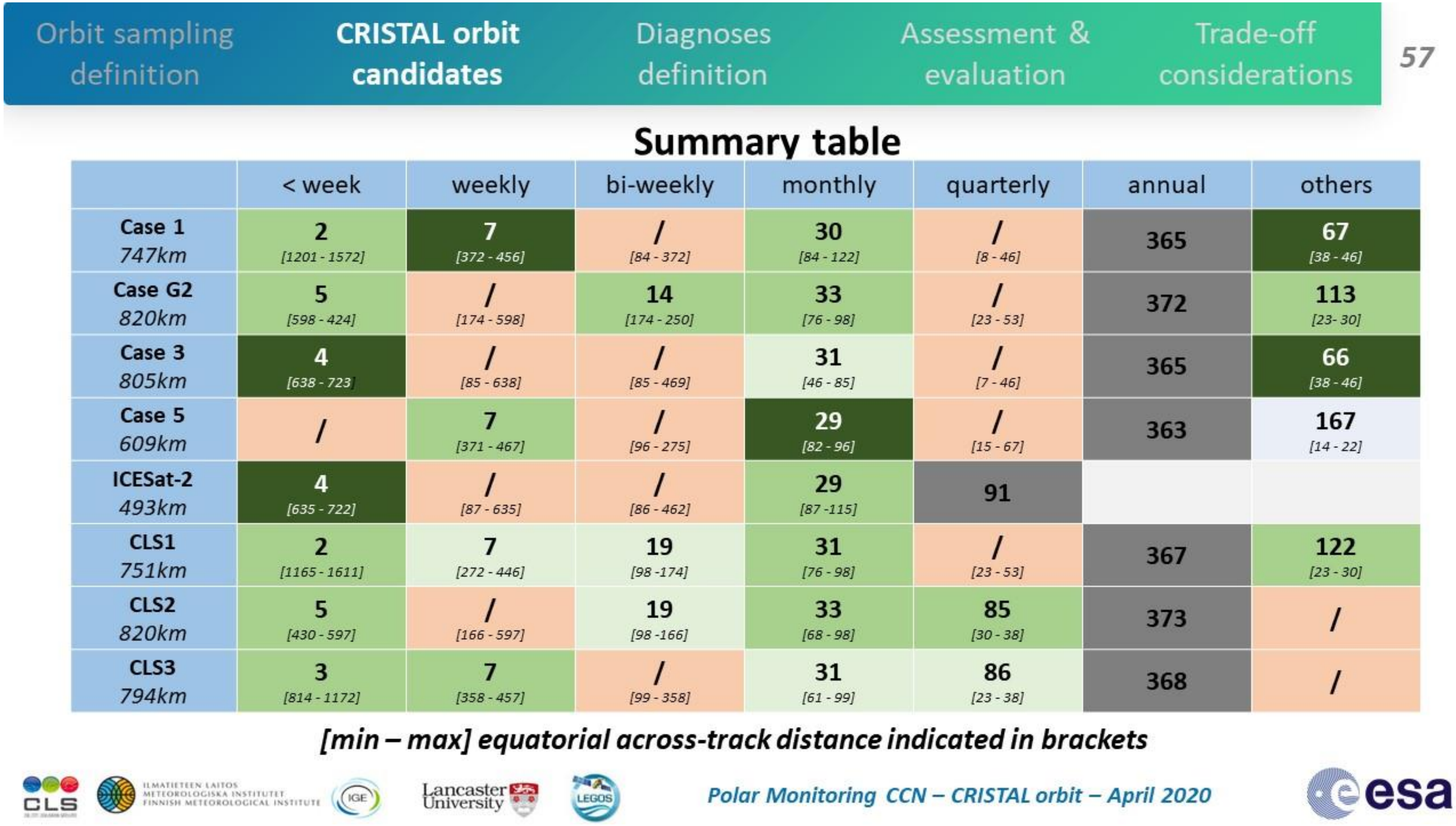
Discussions around Sentinel-3 complementarity for polar mesoscale (& cryosphere)

- **Sentinel-3 constellation provides a rapid homogeneous sampling thanks to the 4 days sub-cycle** (*~400km average across-track resolution with 2 Sentinel-3)*
- Shall we also seek for a 4 days sub-cycle ?

More time needed to look at potential Moiré patterns for each orbit cases

Sentinel-3A/B orbits after 4 days

Sentinel-3A/B orbits after 4 days

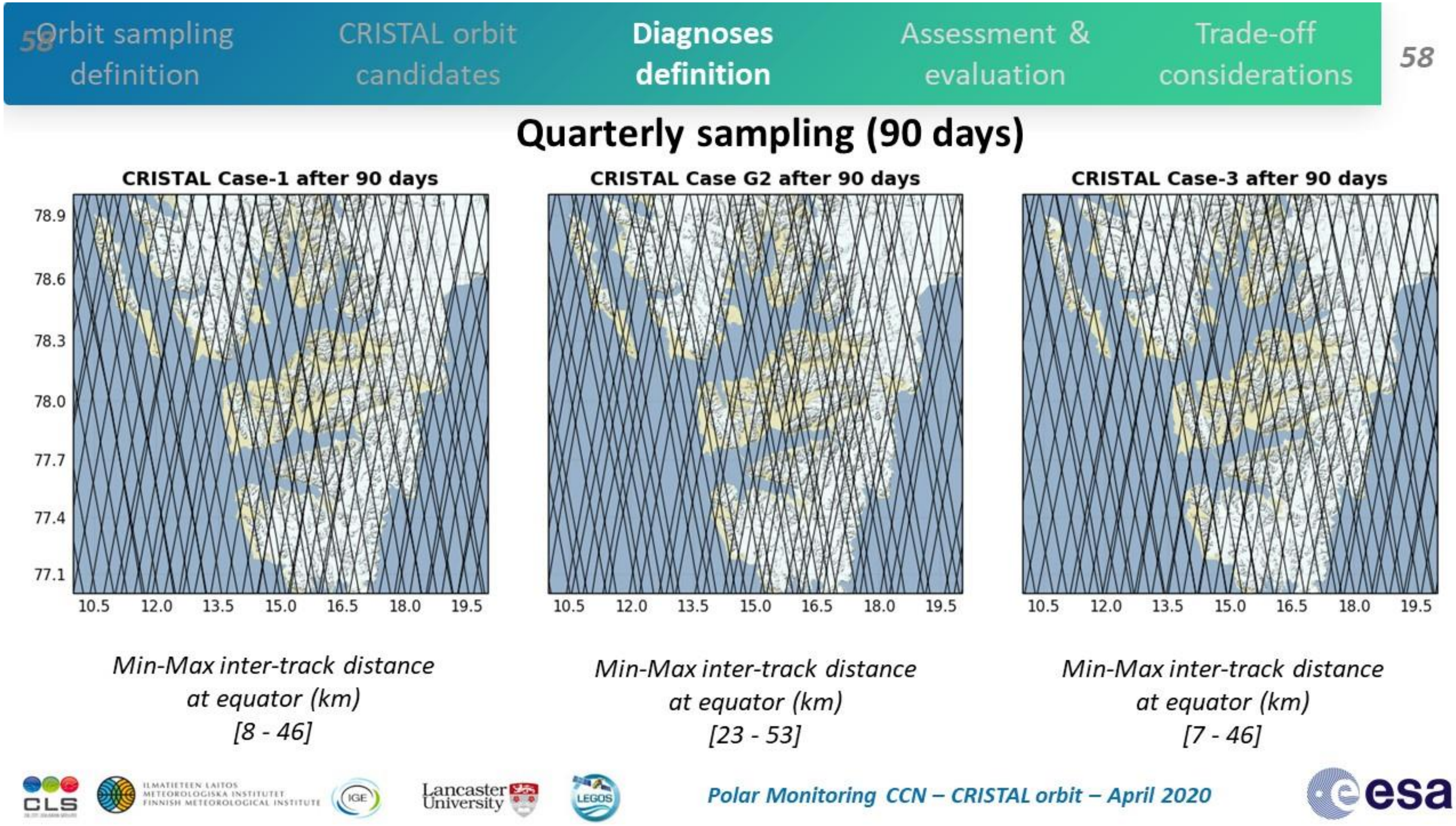


Summary table

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1 *747km*	**2** *[1201 - 1572]*	**7** *[372 - 456]*	**/** *[84 - 372]*	**30** *[84 - 122]*	**/** *[8 - 46]*	**365**	**67** *[38 - 46]*
Case G2 *820km*	**5** *[598 - 424]*	**/** *[174 - 598]*	**14** *[174 - 250]*	**33** *[76 - 98]*	**/** *[23 - 53]*	**372**	**113** *[23- 30]*
Case 3 *805km*	**4** *[638 - 723]*	**/** *[85 - 638]*	**/** *[85 - 469]*	**31** *[46 - 85]*	**/** *[7 - 46]*	**365**	**66** *[38 - 46]*
Case 5 *609km*	**/**	**7** *[371 - 467]*	**/** *[96 - 275]*	**29** *[82 - 96]*	**/** *[15 - 67]*	**363**	**167** *[14 - 22]*
ICESat-2 *493km*	**4** *[635 - 722]*	**/** *[87 - 635]*	**/** *[86 - 462]*	**29** *[87 -115]*	**91**		
CLS1 *751km*	**2** *[1165 - 1611]*	**7** *[272 - 446]*	**19** *[98 -174]*	**31** *[76 - 98]*	**/** *[23 - 53]*	**367**	**122** *[23 - 30]*
CLS2 *820km*	**5** *[430 - 597]*	**/** *[166 - 597]*	**19** *[98 -166]*	**33** *[68 - 98]*	**85** *[30 - 38]*	**373**	**/**
CLS3 *794km*	**3** *[814 - 1172]*	**7** *[358 - 457]*	**/** *[99 - 358]*	**31** *[61 - 99]*	**86** *[23 - 38]*	**368**	**/**

[min – max] equatorial across-track distance indicated in brackets

Polar Monitoring CCN – CRISTAL orbit – April 2020



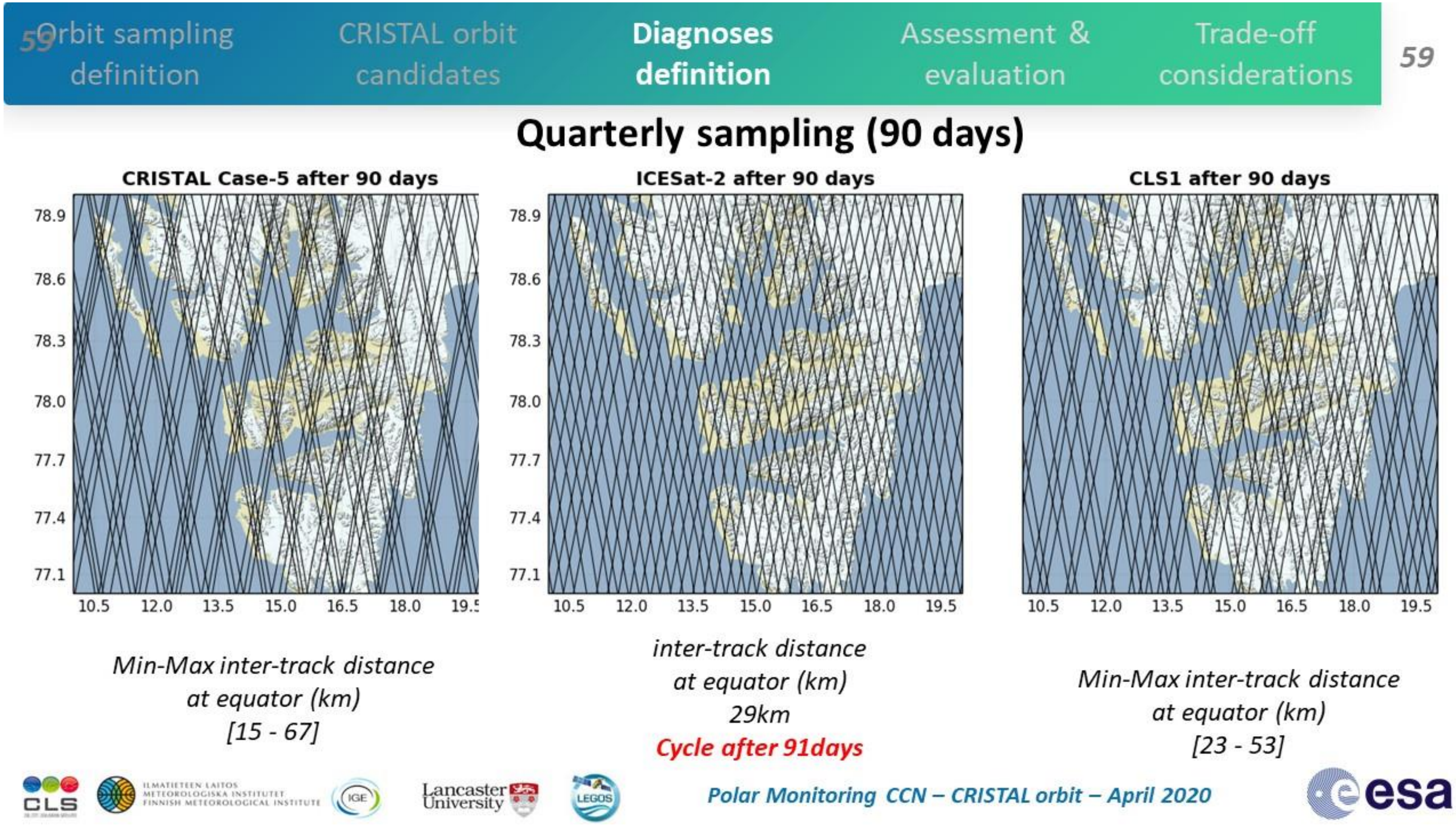
Quarterly sampling (90 days)

Min-Max inter-track distance at equator (km) [8 - 46]

Min-Max inter-track distance at equator (km) [23 - 53]

Min-Max inter-track distance at equator (km) [7 - 46]

Polar Monitoring CCN – CRISTAL orbit – April 2020



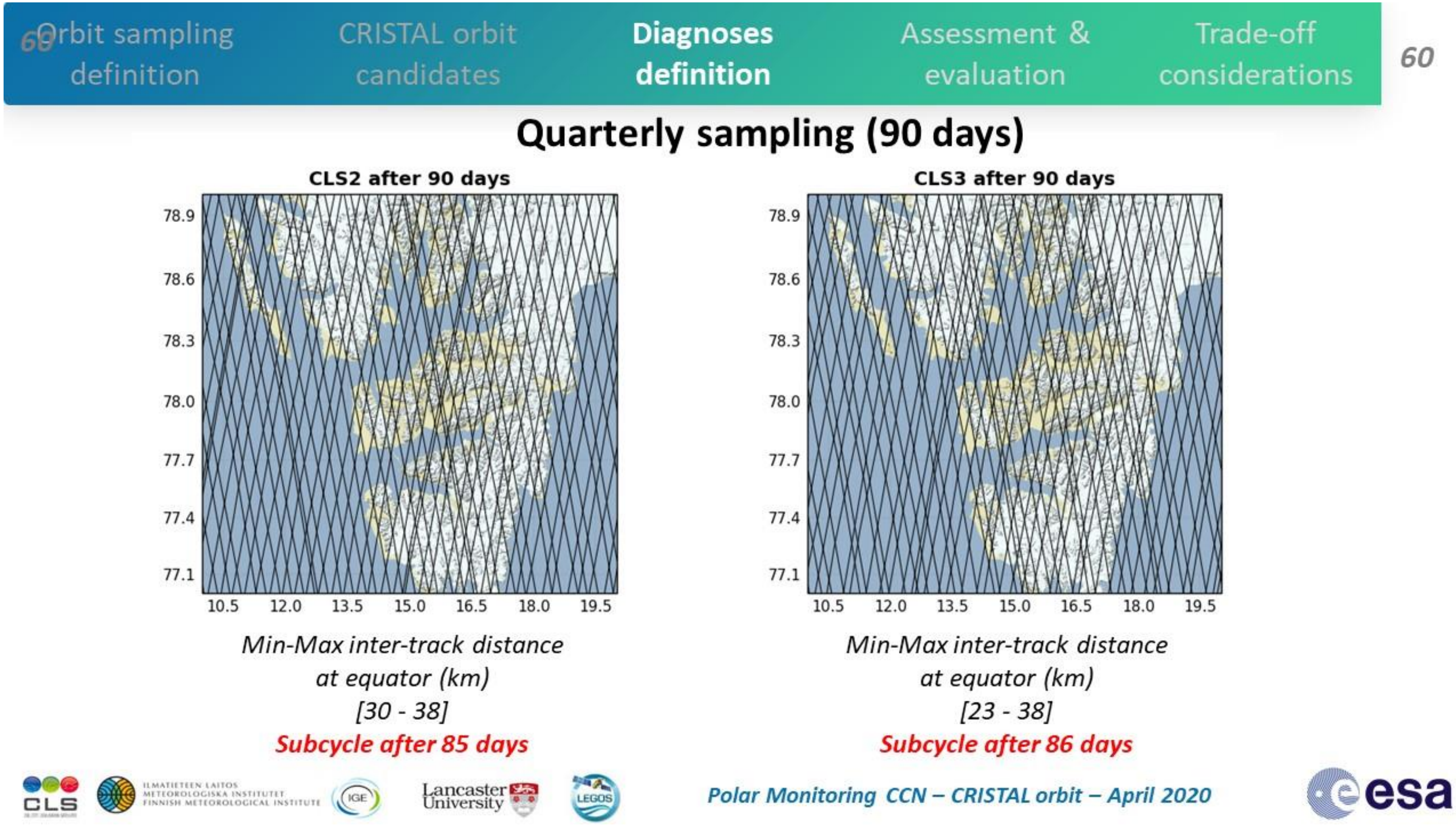
Quarterly sampling (90 days)

Min-Max inter-track distance
at equator (km)
[15 - 67]

inter-track distance
at equator (km)
29km
Cycle after 91days

Min-Max inter-track distance
at equator (km)
[23 - 53]

Polar Monitoring CCN – CRISTAL orbit – April 2020



Orbit sampling definition | CRISTAL orbit candidates | **Diagnoses definition** | Assessment & evaluation | Trade-off considerations

Quarterly sampling (90 days)

CLS2 after 90 days

Min-Max inter-track distance at equator (km)

[30 - 38]

Subcycle after 85 days

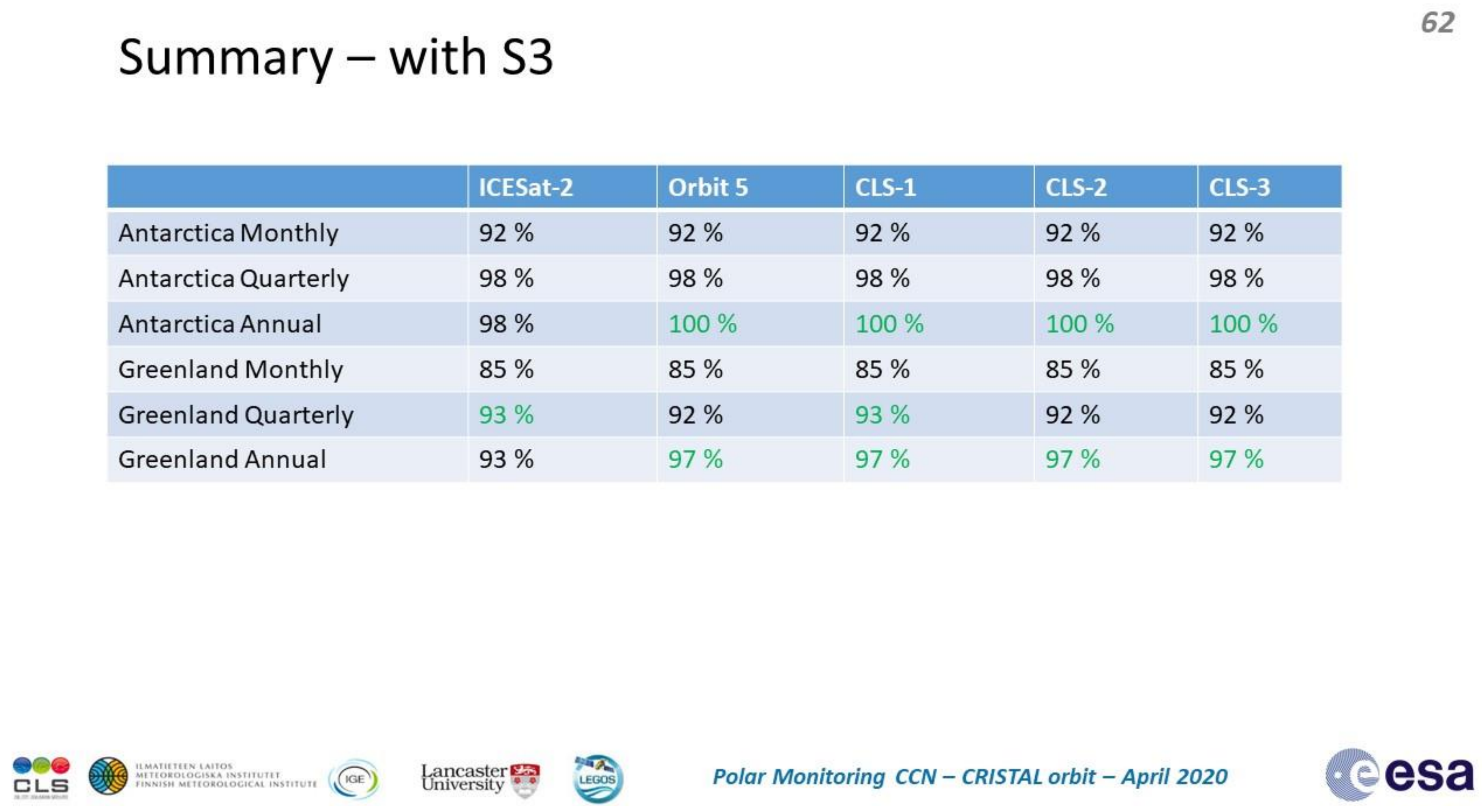
CLS3 after 90 days

Min-Max inter-track distance at equator (km)

[23 - 38]

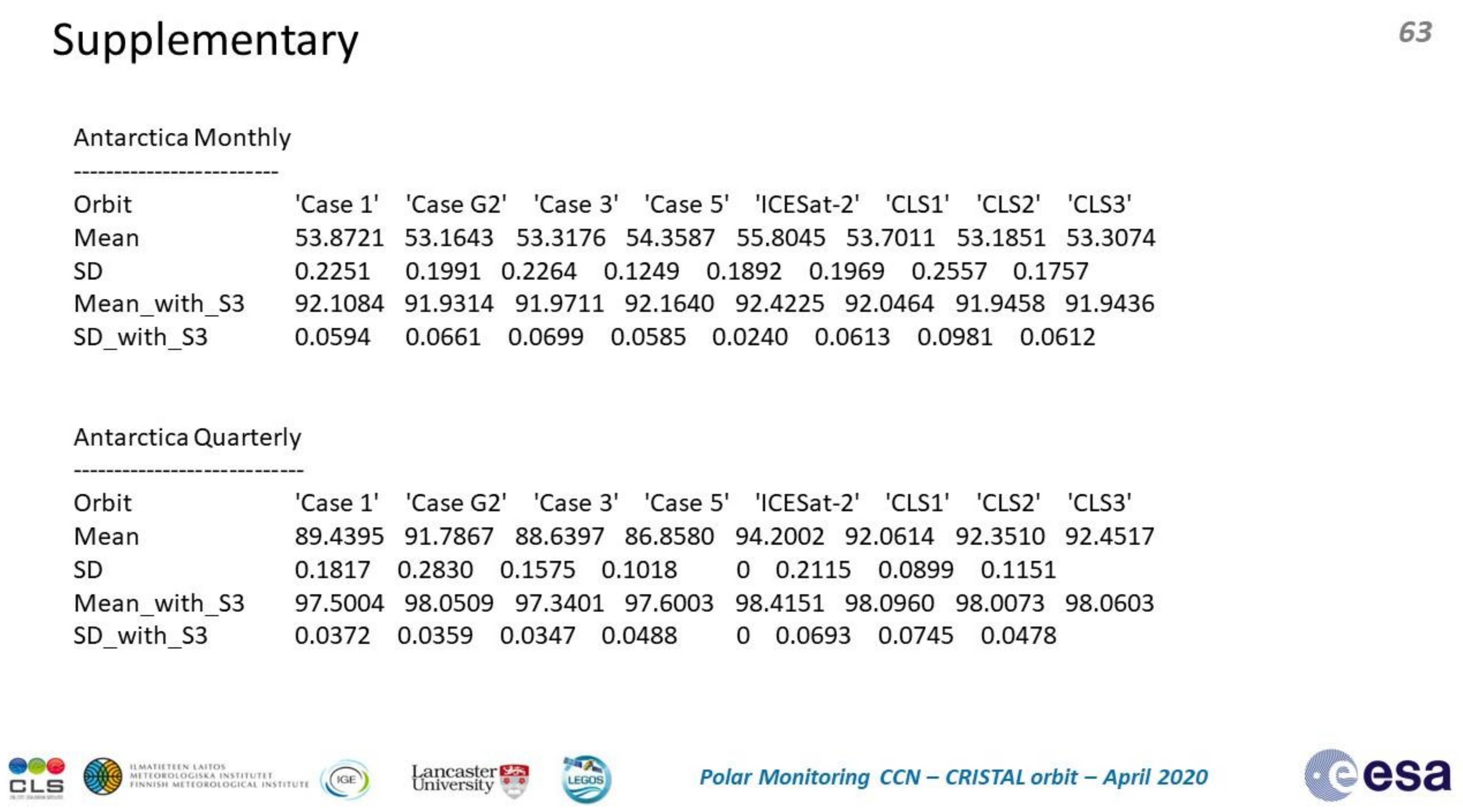
Subcycle after 86 days

Supplementary – Ice sheets



Summary – with S3

	ICESat-2	Orbit 5	CLS-1	CLS-2	CLS-3
Antarctica Monthly	92 %	92 %	92 %	92 %	92 %
Antarctica Quarterly	98 %	98 %	98 %	98 %	98 %
Antarctica Annual	98 %	100 %	100 %	100 %	100 %
Greenland Monthly	85 %	85 %	85 %	85 %	85 %
Greenland Quarterly	93 %	92 %	93 %	92 %	92 %
Greenland Annual	93 %	97 %	97 %	97 %	97 %



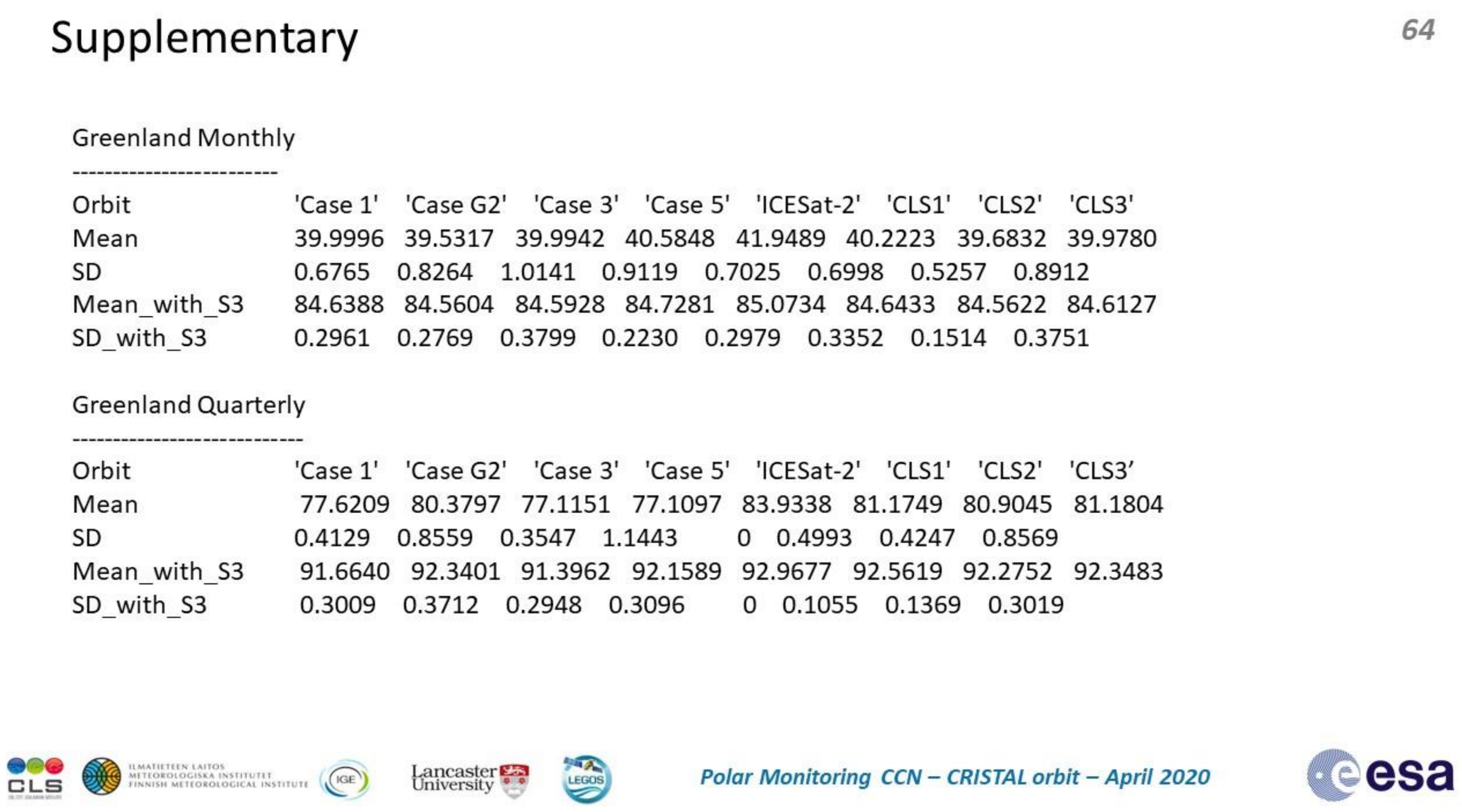
Supplementary

Antarctica Monthly

Orbit	'Case 1'	'Case G2'	'Case 3'	'Case 5'	'ICESat-2'	'CLS1'	'CLS2'	'CLS3'
Mean	53.8721	53.1643	53.3176	54.3587	55.8045	53.7011	53.1851	53.3074
SD	0.2251	0.1991	0.2264	0.1249	0.1892	0.1969	0.2557	0.1757
Mean_with_S3	92.1084	91.9314	91.9711	92.1640	92.4225	92.0464	91.9458	91.9436
SD_with_S3	0.0594	0.0661	0.0699	0.0585	0.0240	0.0613	0.0981	0.0612

Antarctica Quarterly

Orbit	'Case 1'	'Case G2'	'Case 3'	'Case 5'	'ICESat-2'	'CLS1'	'CLS2'	'CLS3'
Mean	89.4395	91.7867	88.6397	86.8580	94.2002	92.0614	92.3510	92.4517
SD	0.1817	0.2830	0.1575	0.1018	0	0.2115	0.0899	0.1151
Mean_with_S3	97.5004	98.0509	97.3401	97.6003	98.4151	98.0960	98.0073	98.0603
SD_with_S3	0.0372	0.0359	0.0347	0.0488	0	0.0693	0.0745	0.0478



Supplementary

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Greenland Monthly
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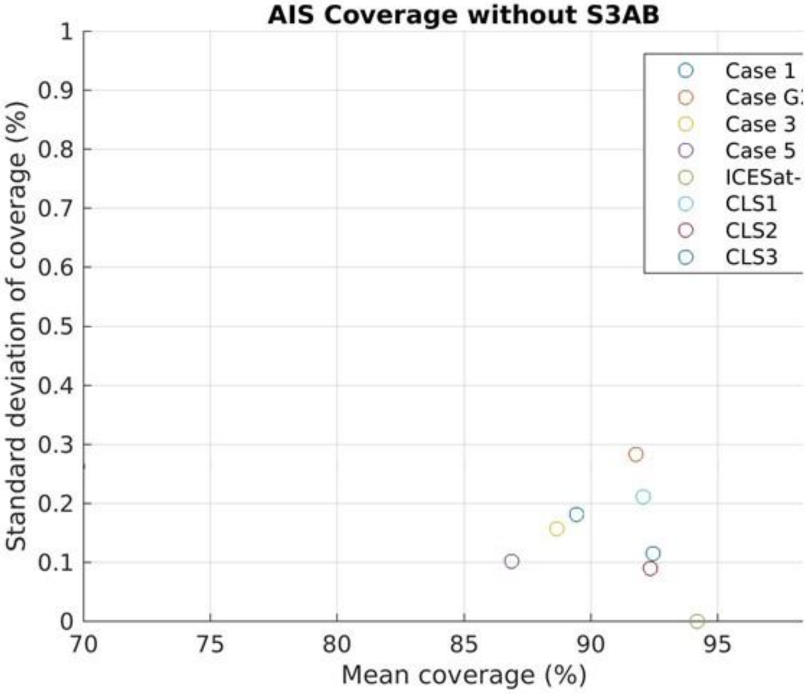
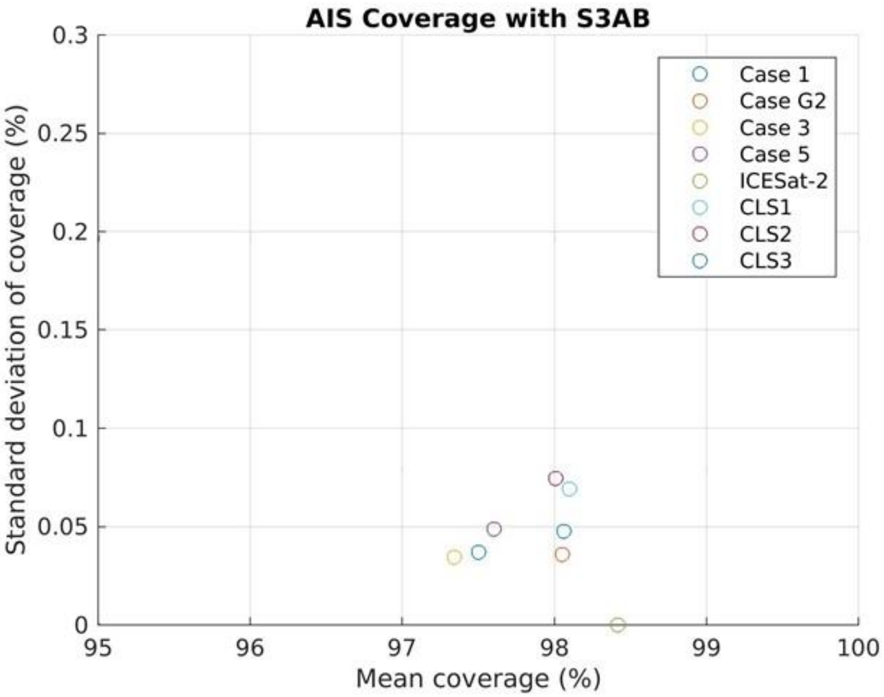
Orbit              'Case 1'   'Case G2'   'Case 3'   'Case 5'   'ICESat-2'   'CLS1'   'CLS2'   'CLS3'
Mean               39.9996   39.5317   39.9942   40.5848   41.9489   40.2223   39.6832   39.9780
SD                 0.6765   0.8264   1.0141   0.9119   0.7025   0.6998   0.5257   0.8912
Mean_with_S3       84.6388   84.5604   84.5928   84.7281   85.0734   84.6433   84.5622   84.6127
SD_with_S3         0.2961   0.2769   0.3799   0.2230   0.2979   0.3352   0.1514   0.3751

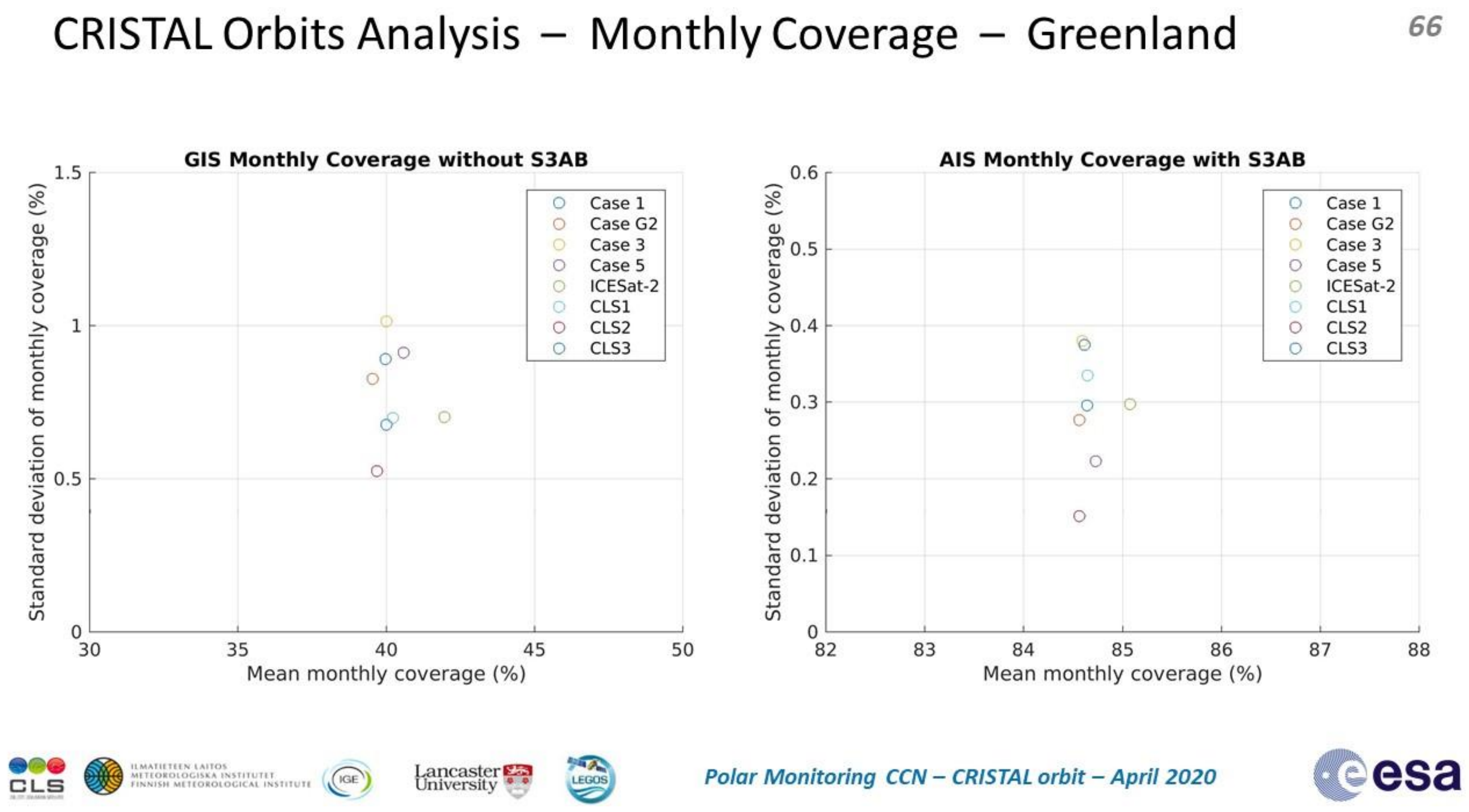
Greenland Quarterly
----------------------------
Orbit              'Case 1'   'Case G2'   'Case 3'   'Case 5'   'ICESat-2'   'CLS1'   'CLS2'   'CLS3'
Mean                77.6209   80.3797   77.1151   77.1097   83.9338   81.1749   80.9045   81.1804
SD                 0.4129   0.8559   0.3547   1.1443        0   0.4993   0.4247   0.8569
Mean_with_S3        91.6640   92.3401   91.3962   92.1589   92.9677   92.5619   92.2752   92.3483
SD_with_S3          0.3009   0.3712   0.2948   0.3096        0   0.1055   0.1369   0.3019
```

CRISTAL Orbits Analysis – Quarterly Coverage – Antarctica



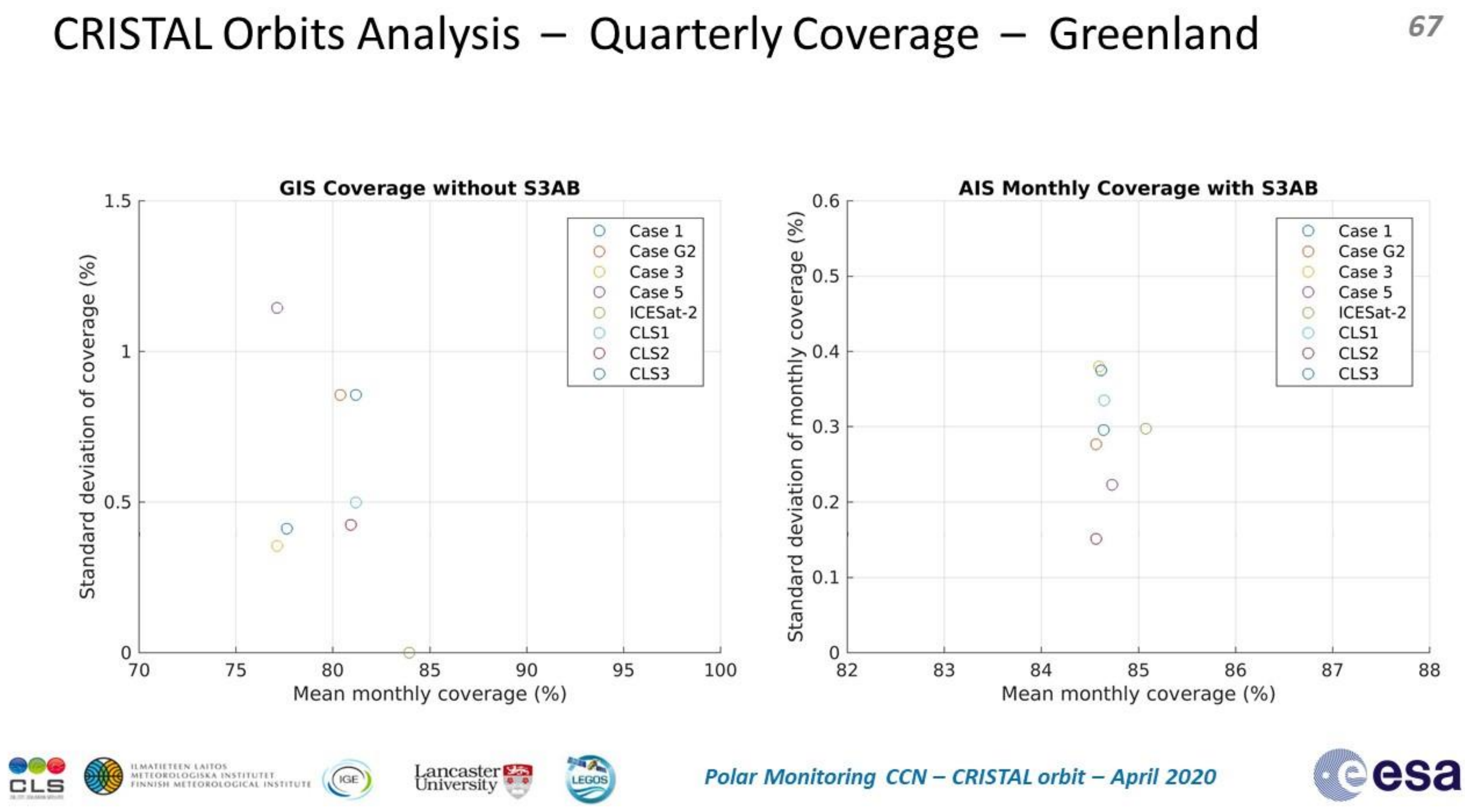


Polar Monitoring CCN – CRISTAL orbit – April 2020



CRISTAL Orbits Analysis – Monthly Coverage – Greenland

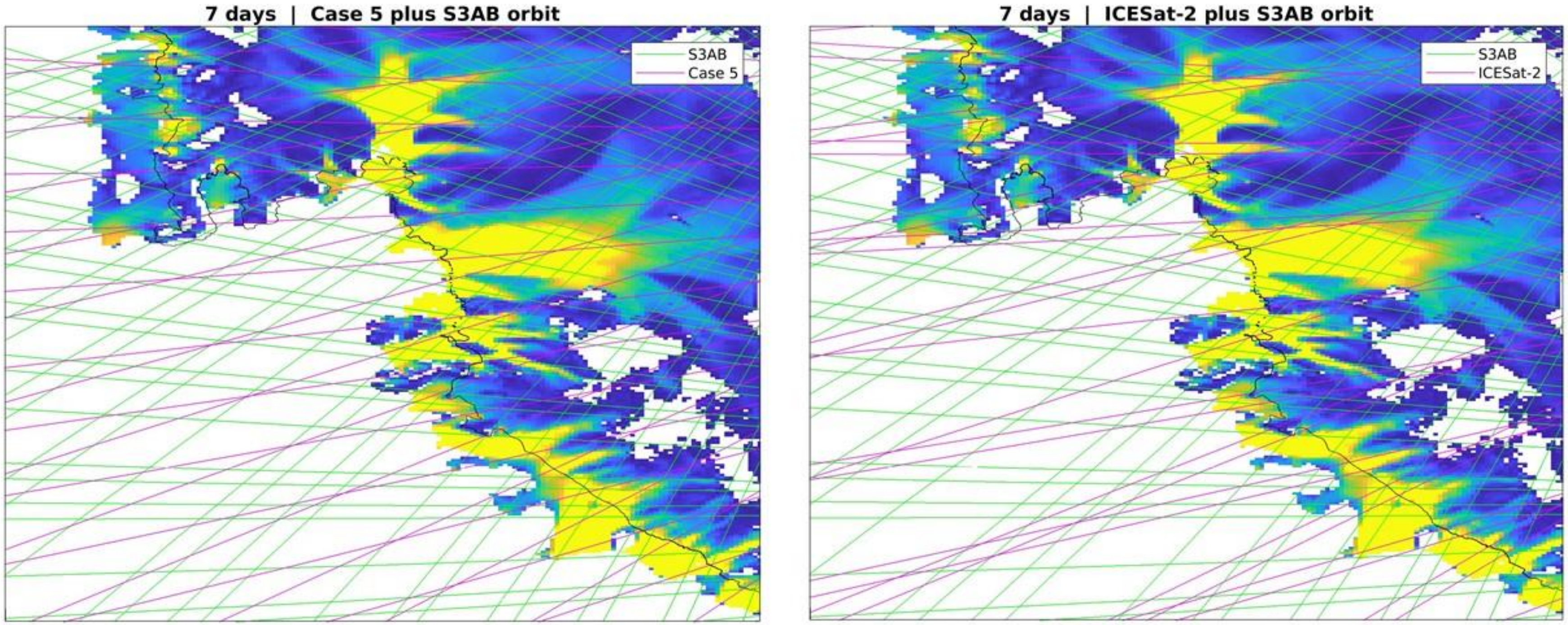
Polar Monitoring CCN – CRISTAL orbit – April 2020



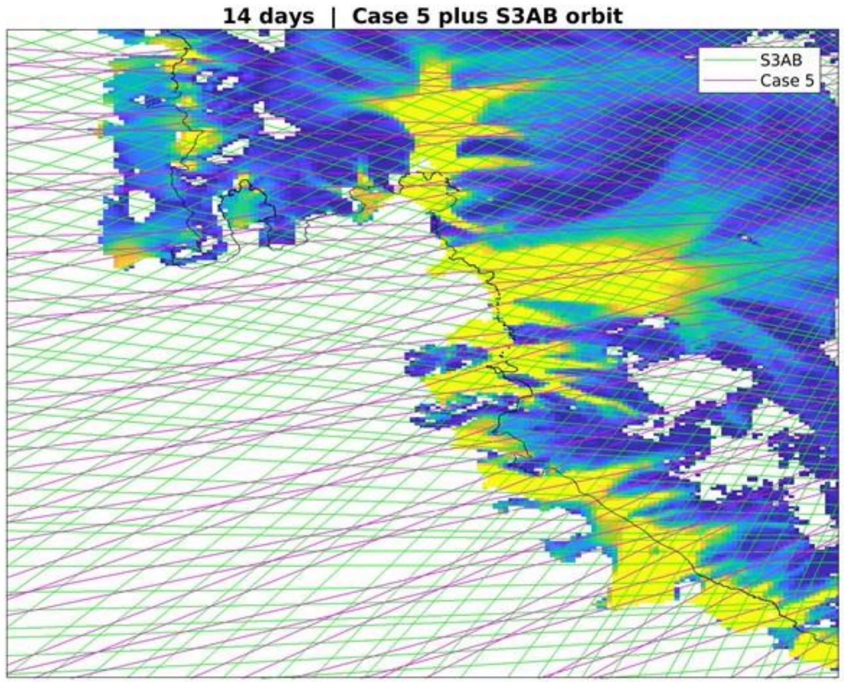
CRISTAL Orbits Analysis – Quarterly Coverage – Greenland

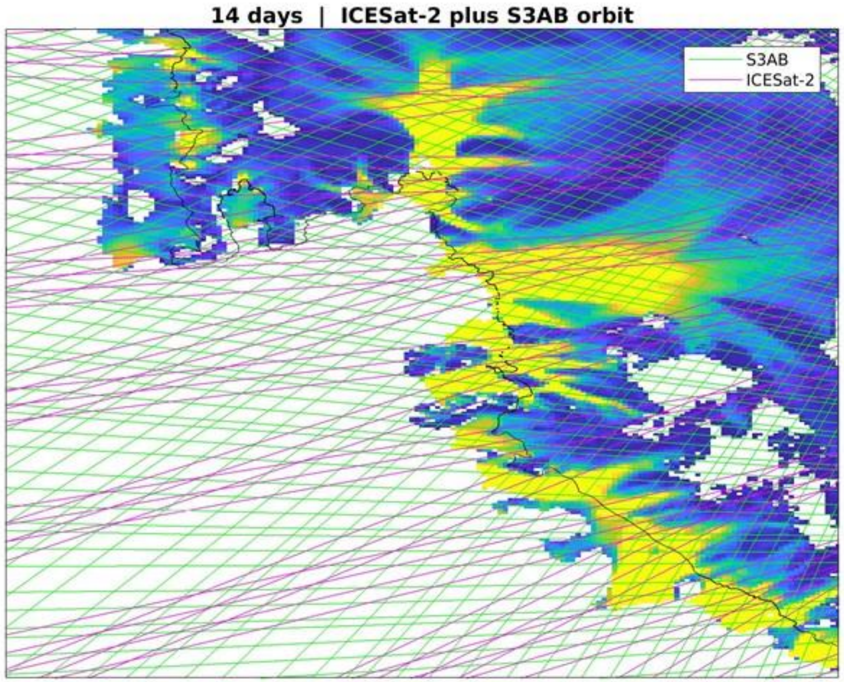
Polar Monitoring CCN – CRISTAL orbit – April 2020

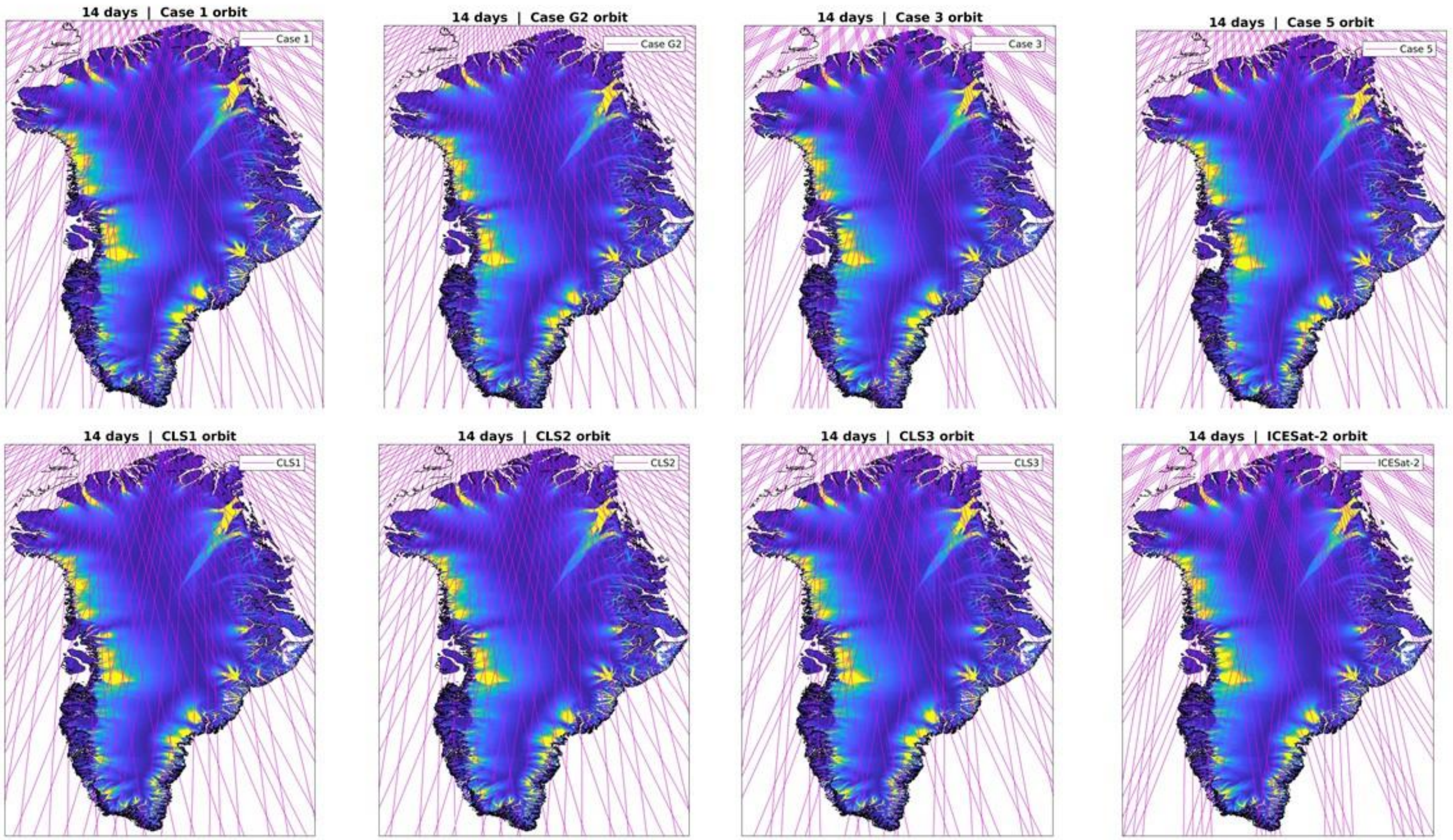
Supplementary - Case 5 vs ICESat-2 - Amundsen Sea - 7 days



Supplementary - Case 5 vs ICESat-2 - Amundsen Sea - 14 days


14 days | Case 5 plus S3AB orbit


14 days | ICESat-2 plus S3AB orbit


14 days | Case 1 orbit
Case 1
14 days | Case G2 orbit
Case G2
14 days | Case 3 orbit
Case 3
14 days | Case 5 orbit
Case 5
14 days | CLS1 orbit
CLS1
14 days | CLS2 orbit
CLS2
14 days | CLS3 orbit
CLS3
14 days | ICESat-2 orbit
ICESat-2

70

Supplementary - Case 5 vs ICESat-2 - 30 days