From GNSS Signal Propagation Effects to Remote Sensing Products in the Central Arctic

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Why signals of Global Navigation Satellite Systems (GNSS)?

- Their propagation effects (scintillation and reflection) give opportunity for remote sensing
- Reflections to sense the Earth surface, scintillations to detect ionospheric irregularities
- Systems with global coverage and a rather inexpensive receiver setup

Why ship-based observations?

- Research vessels (R/V), like the German *Polarstern* (*PS*) and Norwegian *Kronprins Haakon* (*KPH*), can operate in remote areas, e.g. the Central Arctic [Nicolaus et al. 2022]
- Ship-based observations gathered in these areas are helpful to fill gaps in global monitoring, especially of the polar ionosphere
- Ancillary data (e.g. attitude, ocean and atmosphere parameter) are additionally logged on research vessels that help to interpret and validate observations

Methodology:

- For scintillation monitoring: amplitude index S4, phase index σ_ϕ and carrier-to-noise ratio C/N0 are retrieved from high-rate GNSS data [Semmling et al. 2023]
- For sea-ice monitoring: surface reflectivity is retrieved in co-polar (same polarization) and cross-polar component (opposite polarization to incoming signal) [Semmling et al. 2019]
- Reflectivity (cross-polar) is expected to decrease with occurrence and aging of sea-ice

Instrumentation:

- GNSS high-rate receivers with sampling rate at least 10 Hz
- Up-looking antenna and additional side-looking (dual-pol.) antenna for reflections

Challenges:

- Movement of the ship increases uncertainties in the retrieval
- Field-of-view to direct and reflected GNSS signals has to be optimized on the ship

Fram Strait Cruise 2020

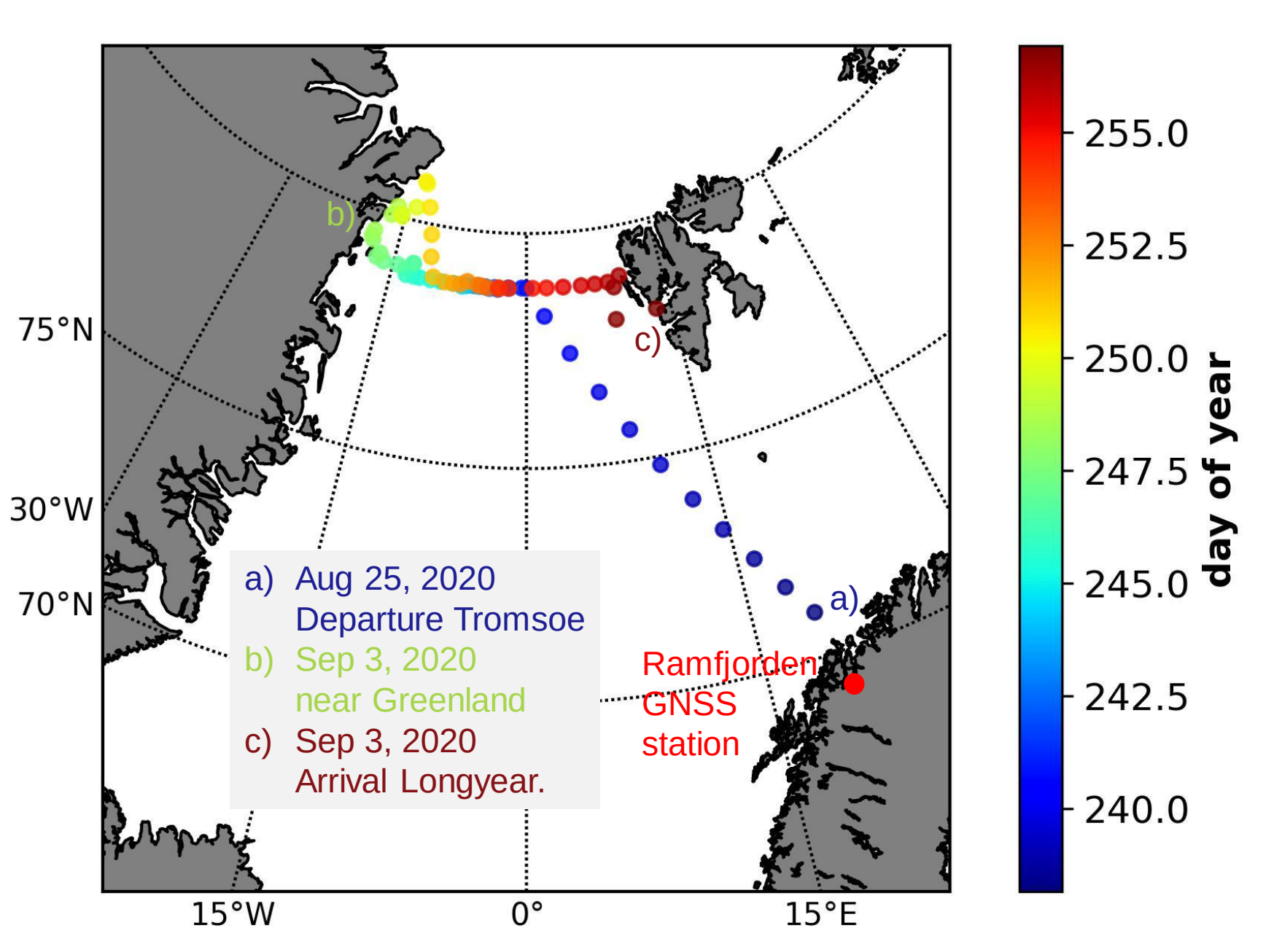


Fig. 1: Fram Strait cruise of *KPH* in late summer 2020.

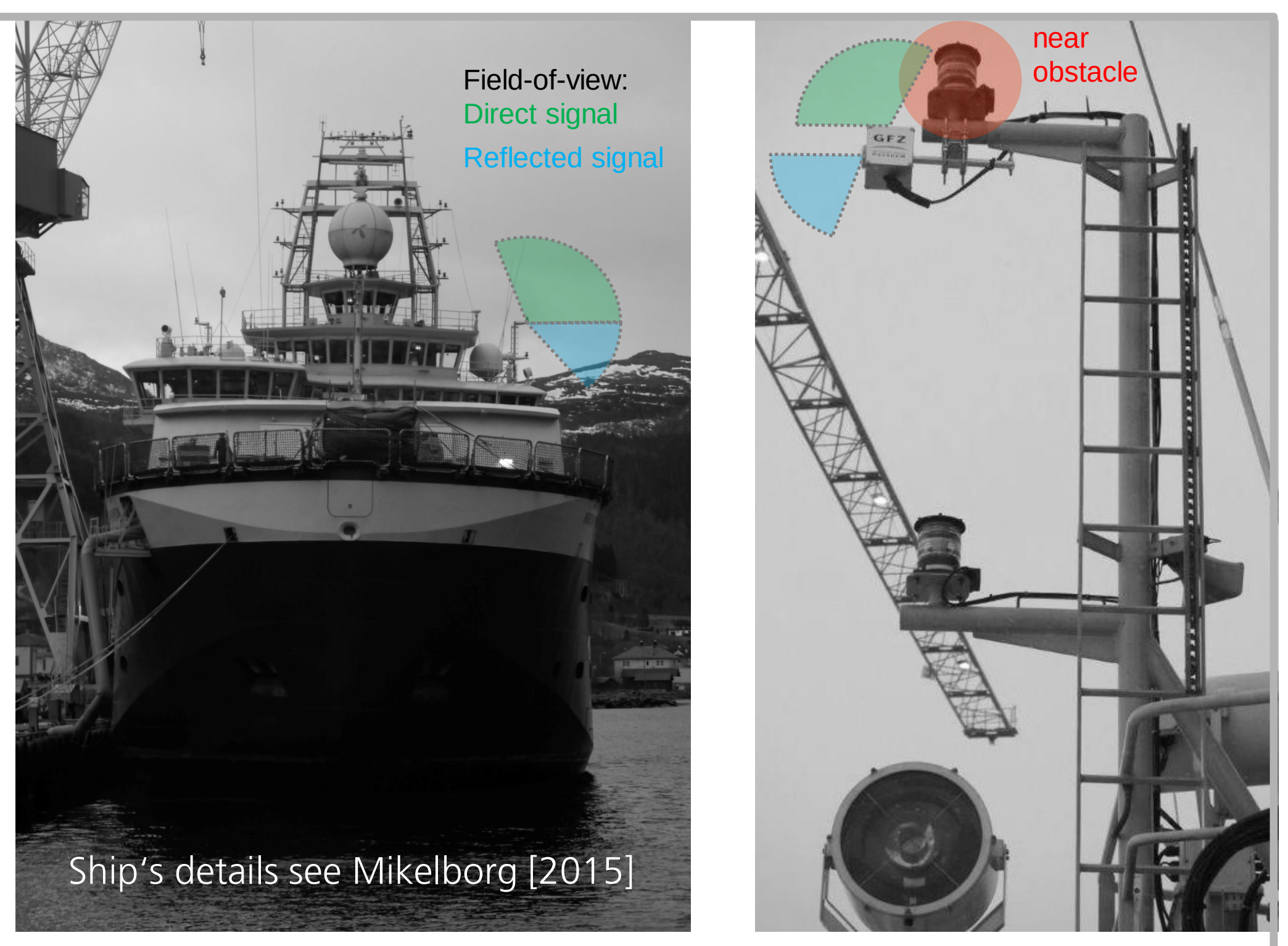


Fig. 2: GNSS antenna setup installed aboard R/V *Kronprins Haakon*.

MOSAiC Expedition 2019/2020

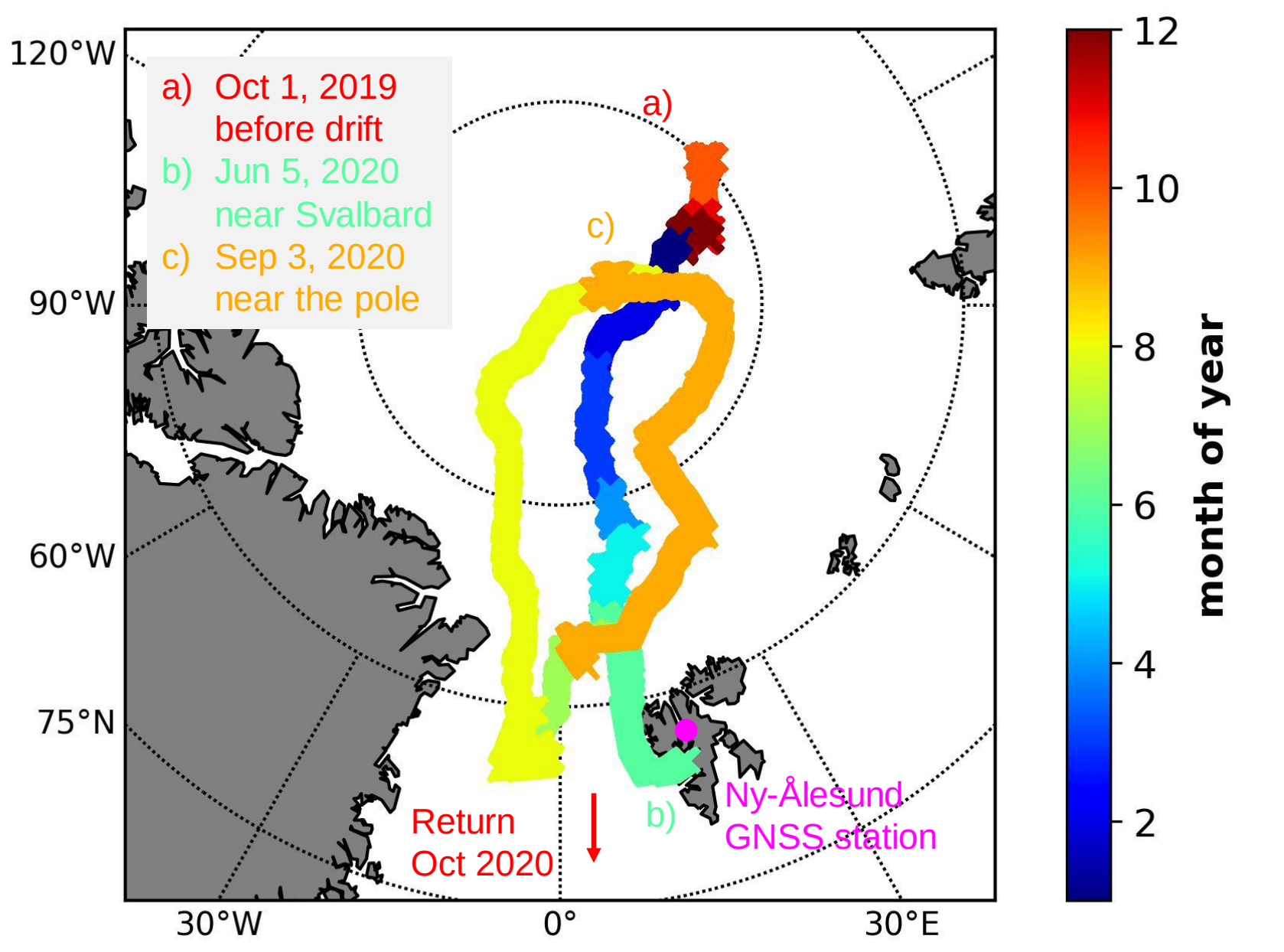
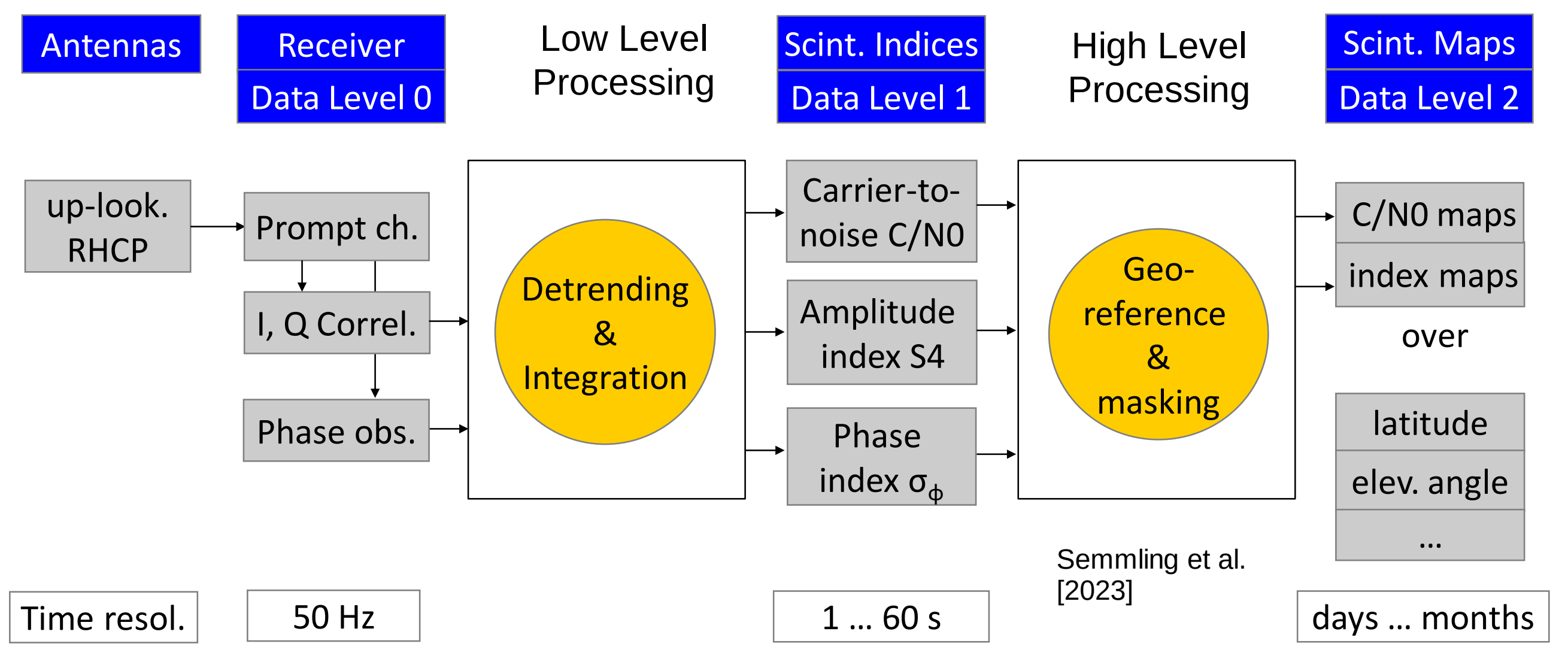


Fig. 3: MOSAiC expedition of *PS* over one year (2019/2020).

Fig. 4: GNSS antenna setup installed for MOSAiC on R/V *Polarstern*.

A: Ionosphere Scintillation Monitoring



Antennas
Receiver
Data Level 0
Low Level Processing
Scint. Indices
Data Level 1
High Level Processing
Scint. Maps
Data Level 2
up-look. RHCP
Prompt ch.
I, Q Correl.
Phase obs.
Detrending & Integration
Carrier-to-noise C/N0
Amplitude index S4
Phase index σ_ϕ
Geo-reference & masking
C/N0 maps
index maps
over
latitude
elev. angle
...
Semmling et al. [2023]
Time resol.
50 Hz
1 ... 60 s
days ... months

Fig. A.1: Processing scheme of high-rate GNSS data for ionosphere scintillation monitoring.

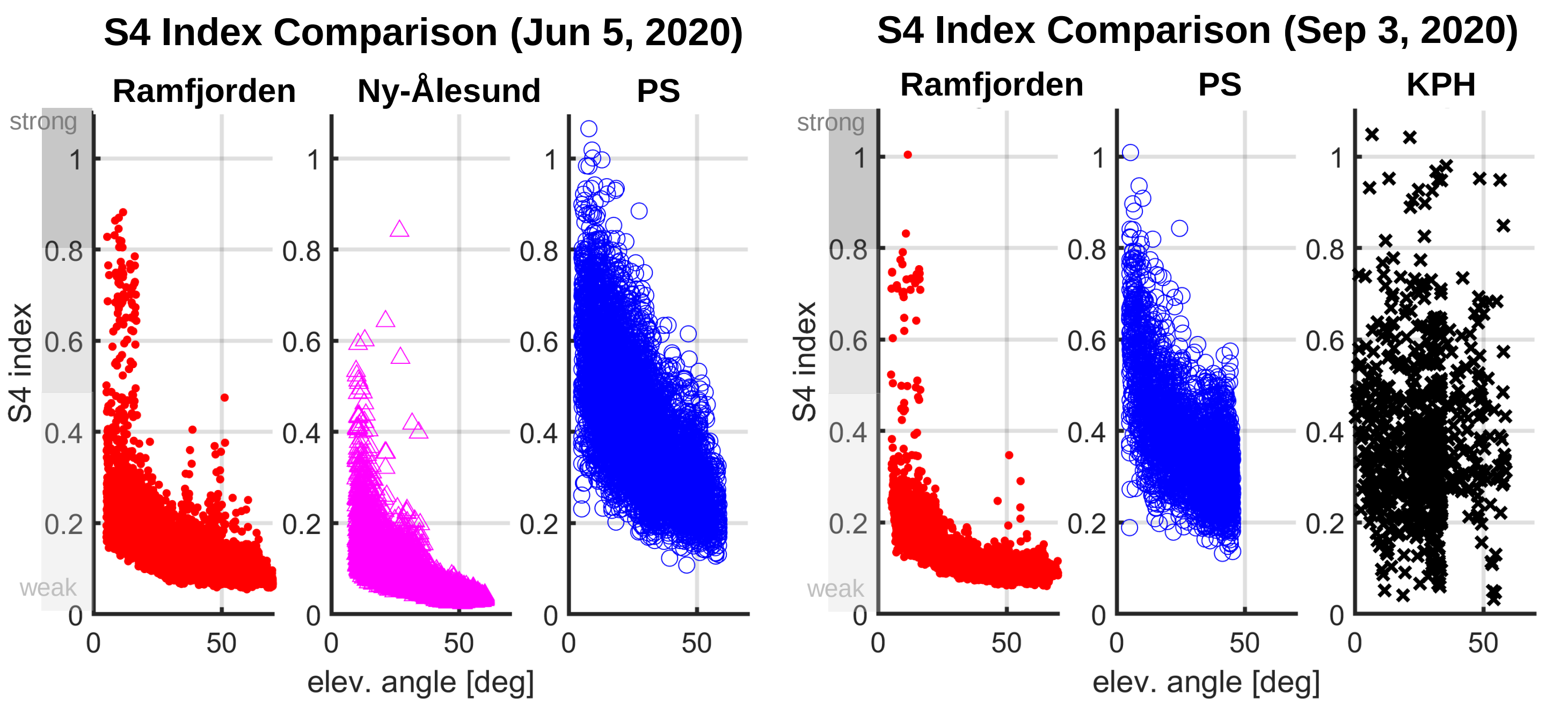


Fig. A.2: Selected days for comparison of S4 results considering GNSS station and ship data. Left: Ramfjorden, Ny-Ålesund station data to *PS* ship data. Right: Ramfjorden station data to *PS* and *KPH* ship data. All ship data, here, under calm sea state conditions.

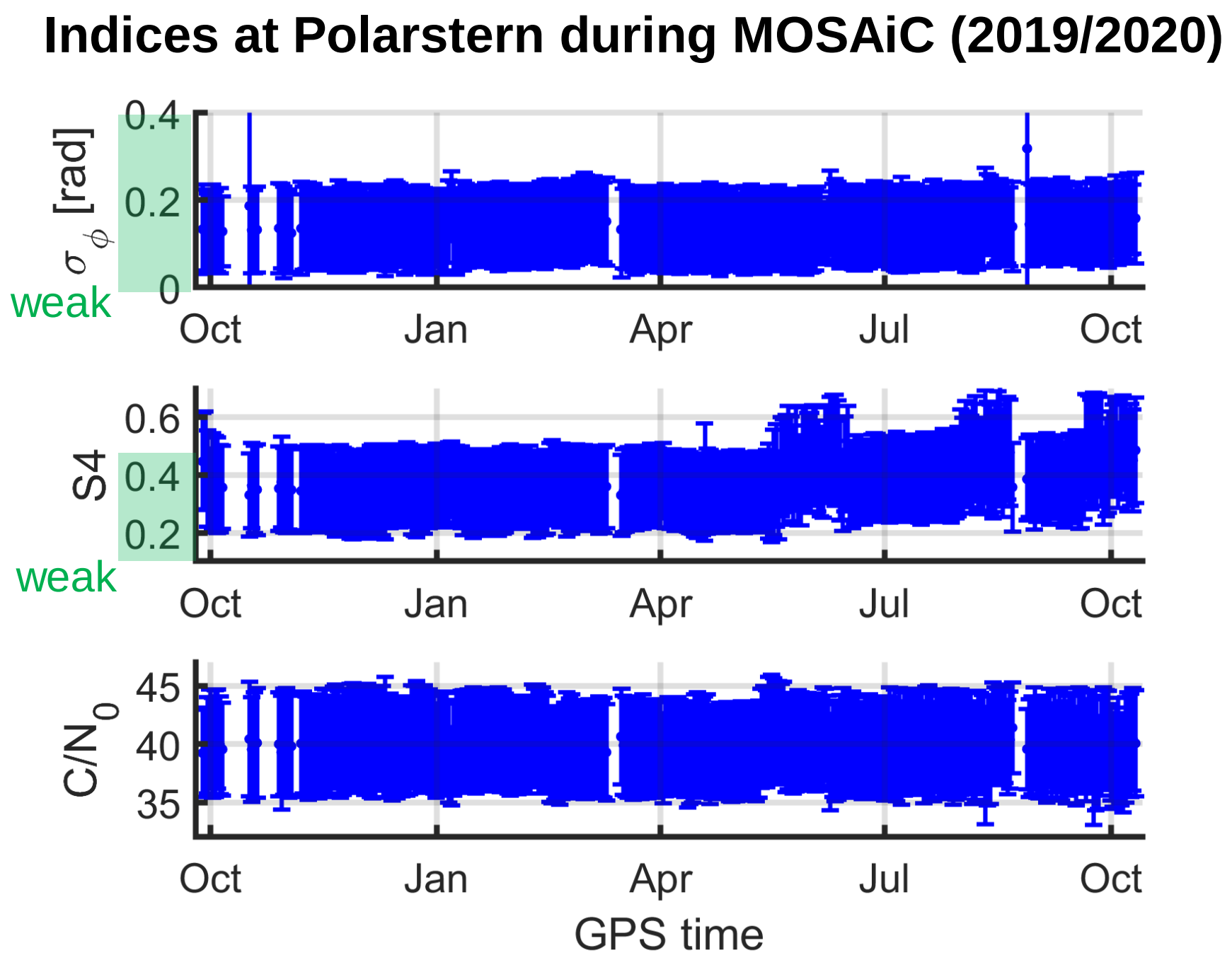
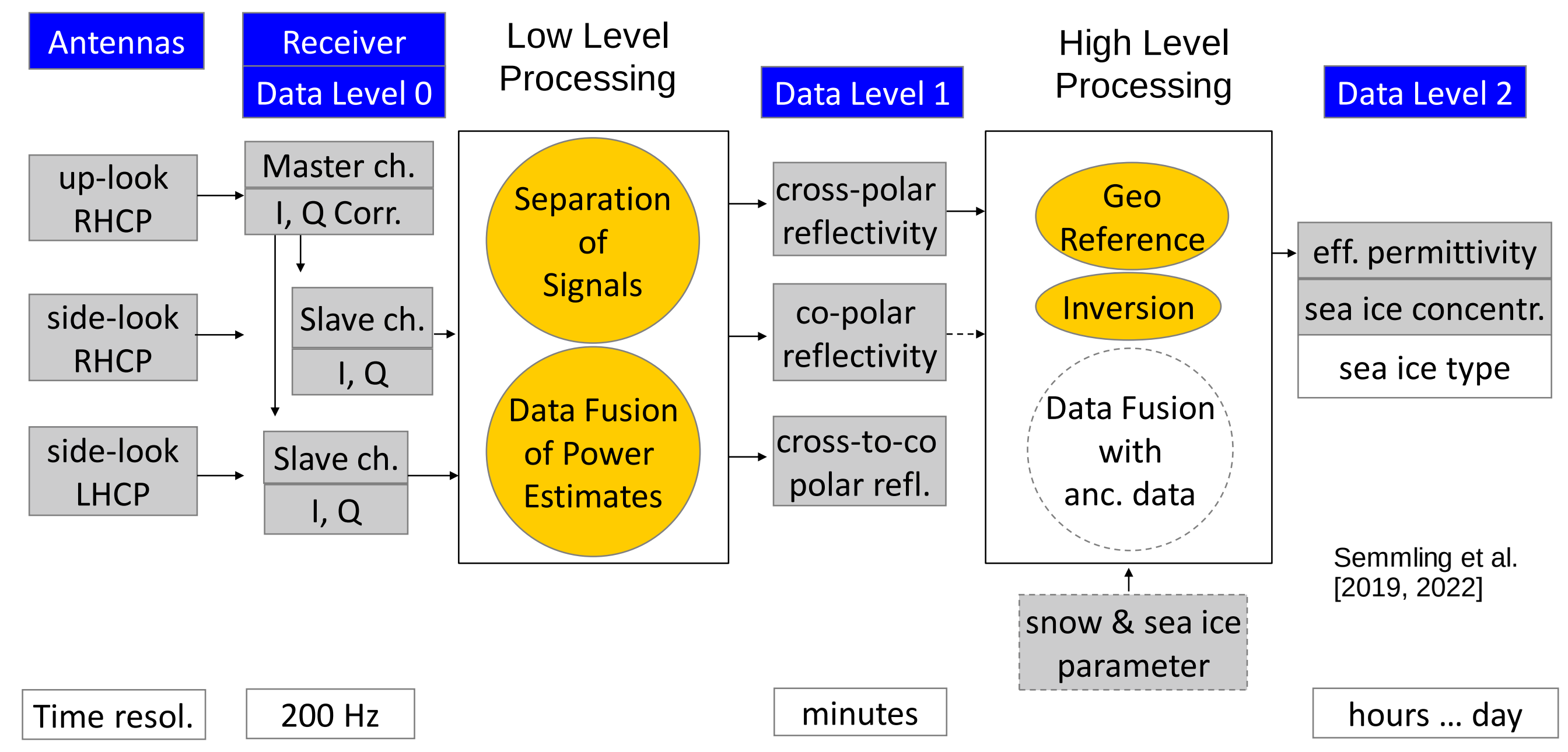


Fig. A.3: All-year plots of scintillation indices and carrier-to-noise ratio at *PS*. Daily averages with stand. dev. range.

B: Sea-ice Monitoring



Antennas
Receiver
Data Level 0
Low Level Processing
Data Level 1
High Level Processing
Data Level 2
up-look RHCP
side-look RHCP
side-look LHCP
Master ch.
I, Q Corr.
Slave ch.
I, Q
Slave ch.
I, Q
Separation of Signals
Data Fusion of Power Estimates
cross-polar reflectivity
co-polar reflectivity
cross-to-co polar refl.
Geo Reference
Inversion
Data Fusion with anc. data
snow & sea ice parameter
eff. permittivity
sea ice concentr.
sea ice type
Semmling et al. [2019, 2022]
Time resol.
200 Hz
minutes
hours ... day

Fig. B.1: Processing scheme of GNSS reflectometry data for sea-ice monitoring.

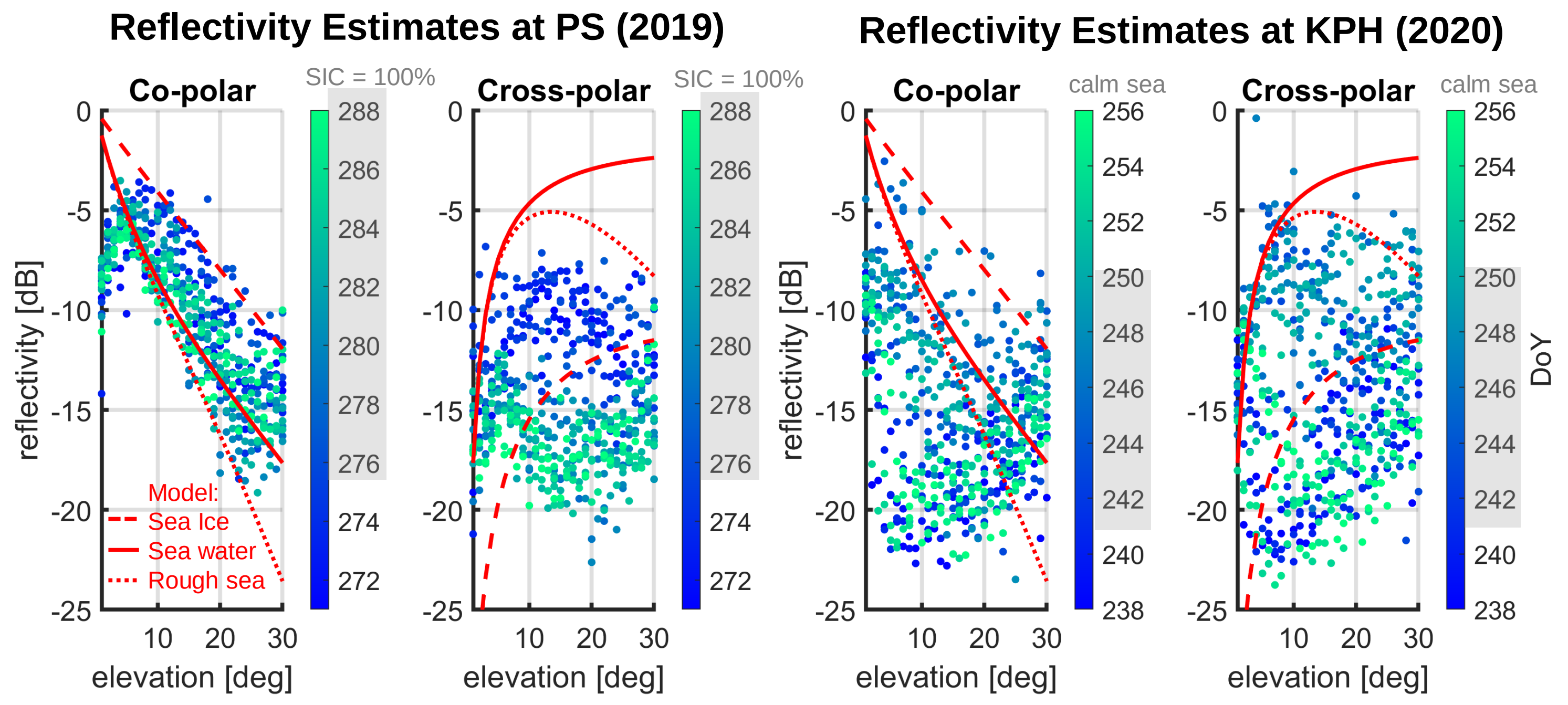


Fig. B.2: Estimates of daily reflectivity profiles compared to model predictions. Left: 17 days of *PS* entering the sea ice in autumn 2019, cross-polar profiles are clearly sensitive to ice occurrence (decrease in reflectivity). Right: 18 days of *KPH*'s Fram Strait cruise in late summer 2020. These estimates show large spread but are still sensitive to calm sea state with highest reflectivity for DoY 241 … 250.

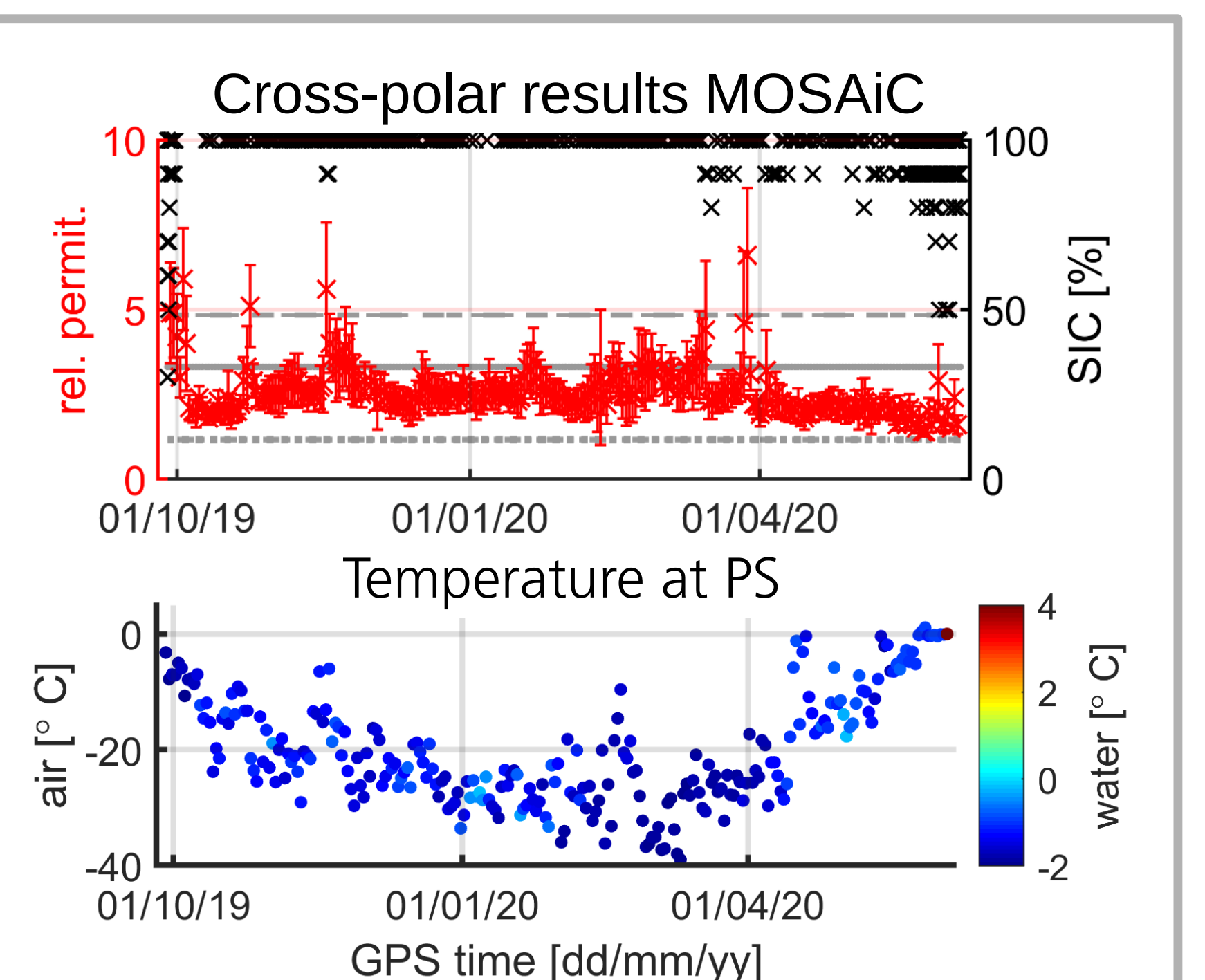


Fig. B.3: Estimates of surface relative permittivity during the first ice-drift period of MOSAiC with relation to sea-ice concentration (SIC) and temperature

Discussion of Scintillation Results:

- S4 index decreases, in general, with increasing elev. angle (Fig. A.2), shorter atmosphere path lengths
- Ship-based S4 is increased comp. to station S4 data, due to impact of multipath and ship movement
- *PS* setup still sensitive to moderate and strong scintillations, *KPH* data disturbed (sensitivity lost)
- Overall calm ionospheric conditions during MOSAiC, average indices in weak regime (Fig. A.3)

Discussion of Sea-ice Results:

- Cross-polar reflectivity profiles are sensitive to occurrence of sea ice (Fig. B.2, *PS* profiles)
- Spread in *KPH* profiles increased, still sensitive to sea state conditions (Fig. B.2)
- *PS* data provides time series of permittivity estimates for eight-month drift period (Fig. B.3)
- Ice penetration bias of estimates late in the drift period of *PS* (April, May 2020)

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