

Atmospheric correction for turbid and complex waters

Quinten Vanhellemont
2026 IOCCG Summer Lecture Series

Turbid and complex waters

Issues with atmospheric correction

Solutions?

Turbid and complex waters

Complex waters are perhaps best described as complex conditions that invalidate processing assumptions



Venice
S2C/MSI
2026-03-28

~15x15 km
 ρ s RGB



Rhone Plume
S2B/MSI
2026-02-17

~15x15 km
 ρ_s RGB

Suriname
S2B/MSI
2026-06-20



~15x15 km
ps RGB

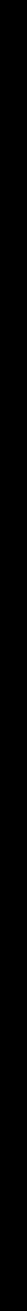


Kaliyakheri
S2B/MSI
2026-02-06

~15x15 km
ps RGB

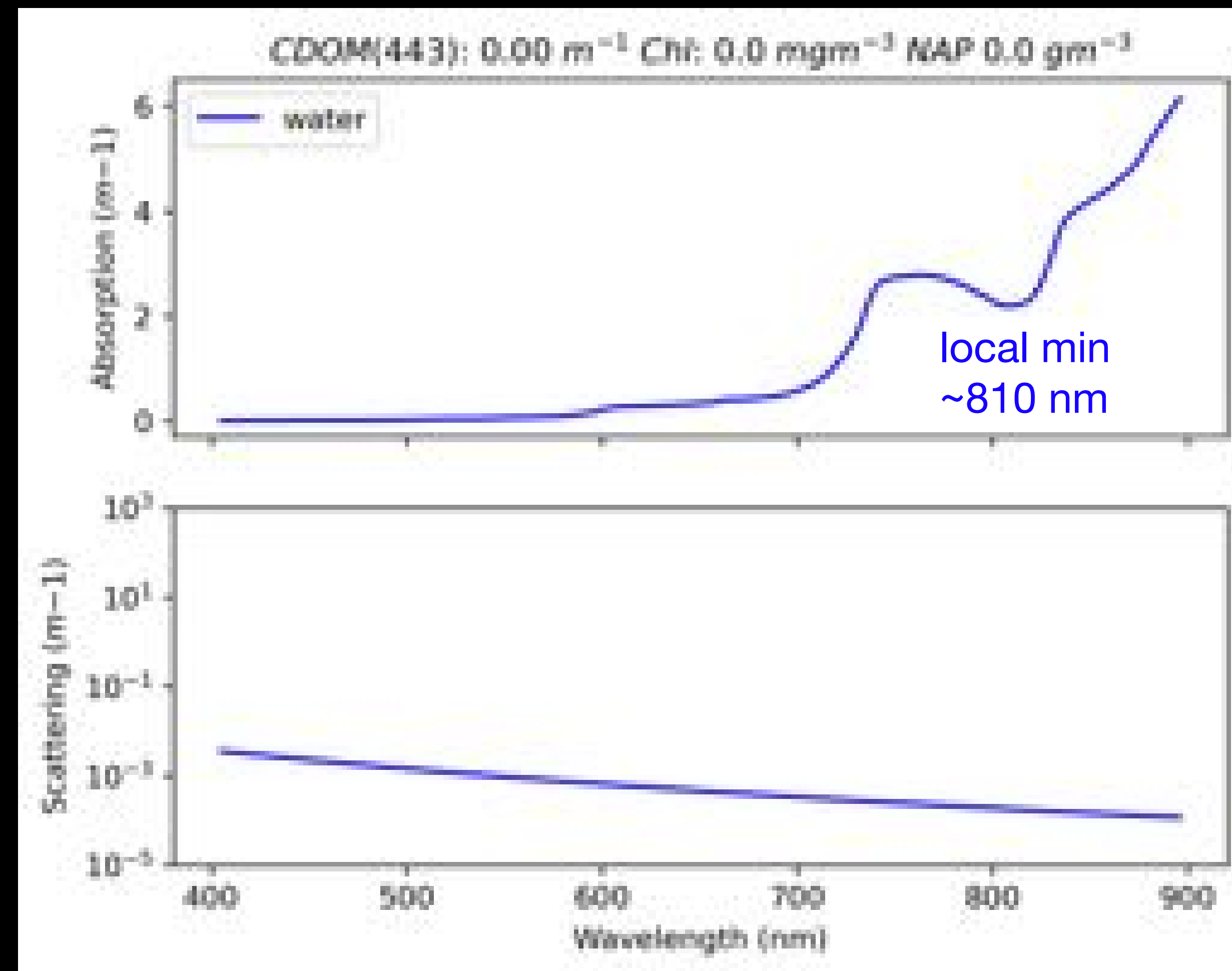
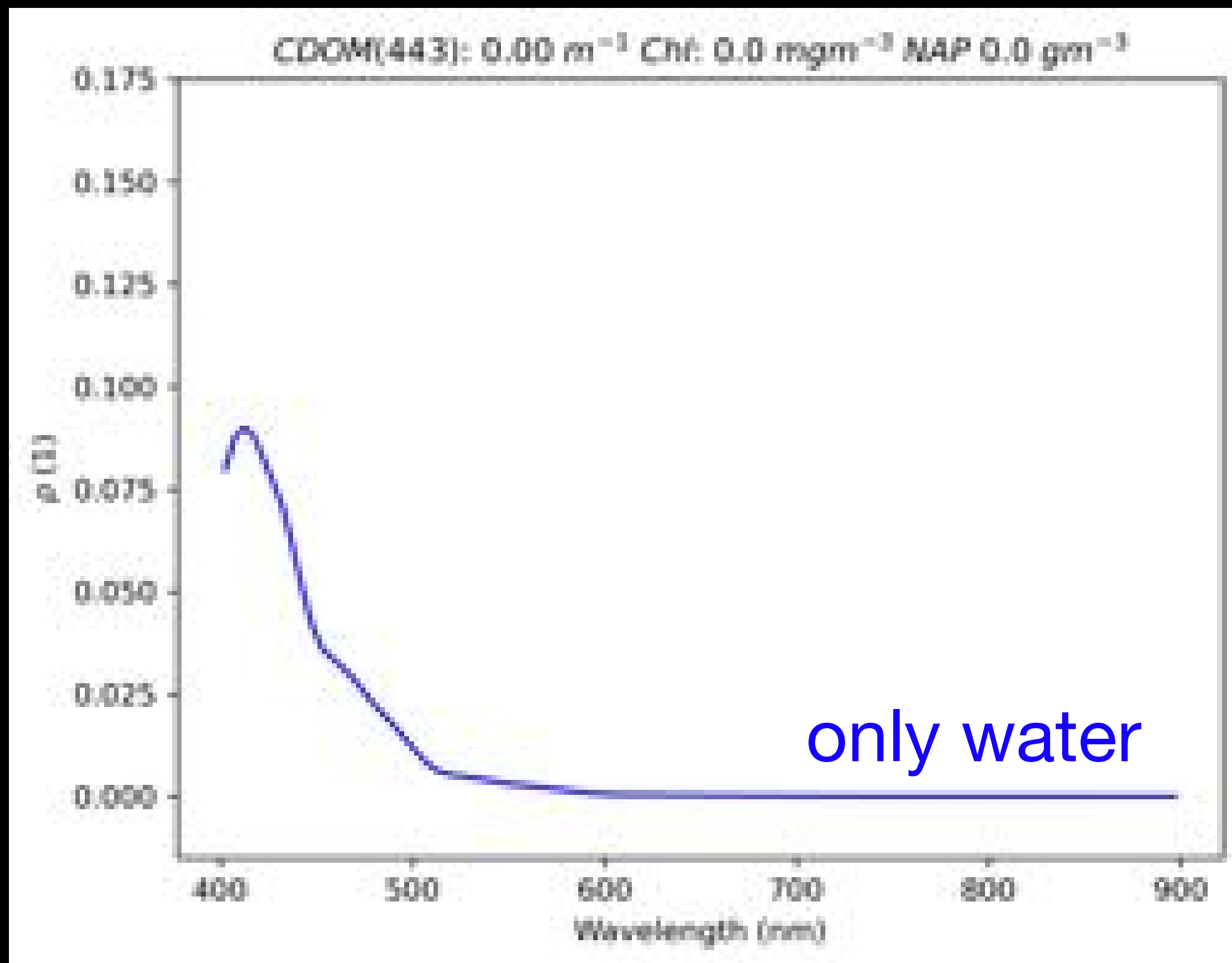
Turbid and complex waters

- Reflectance of a water target varies as a result of the Inherent Optical Properties (IOPs) of different components present in the water (and the bottom reflectance if not optically deep)
- The water reflectance can be modeled by including four components: water, phytoplankton pigments (e.g. chlorophyll a, CHL), coloured dissolved organic matter (CDOM), and non-algal particles (NAP)



$$\rho_w = \pi \times R_{rs}$$

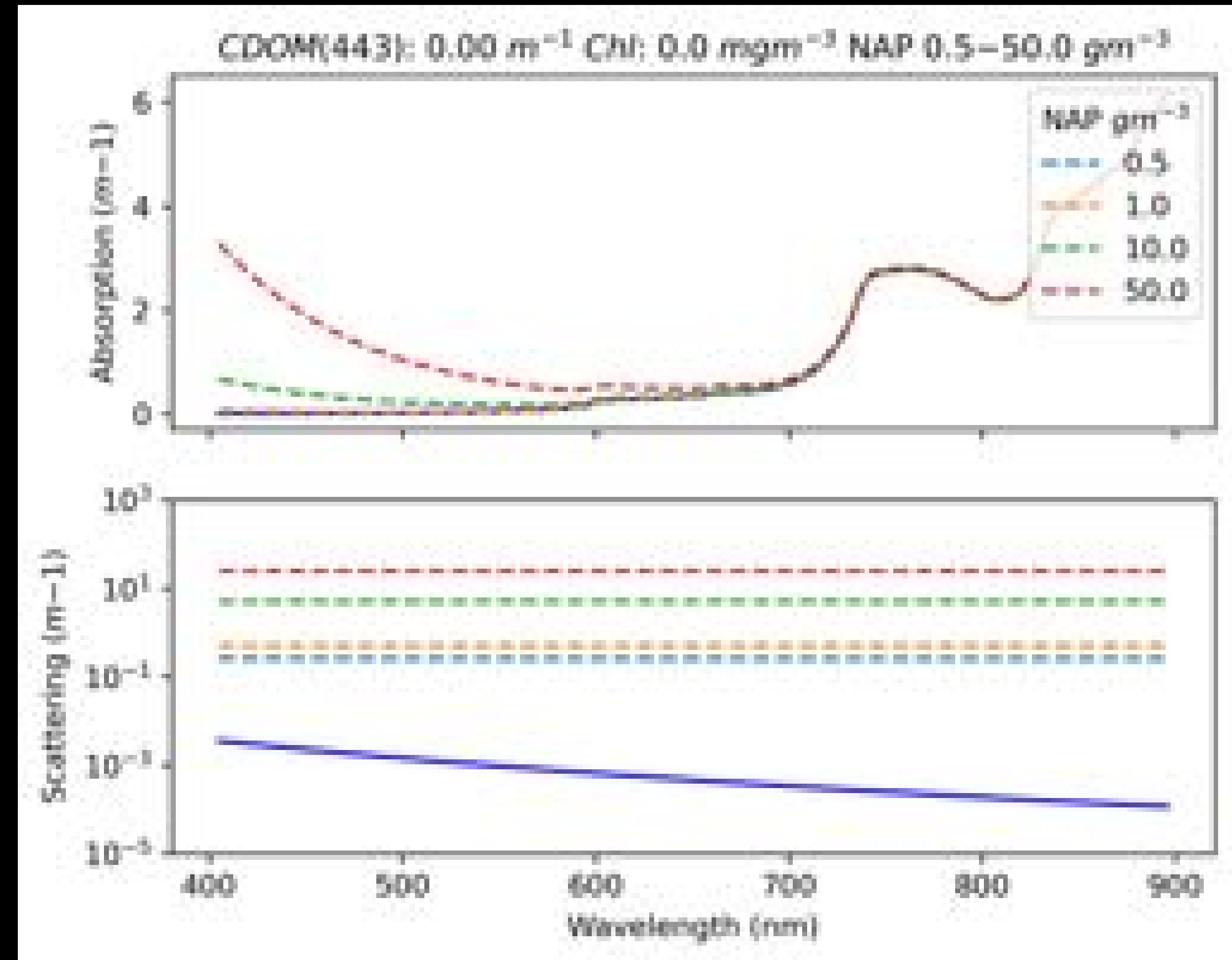
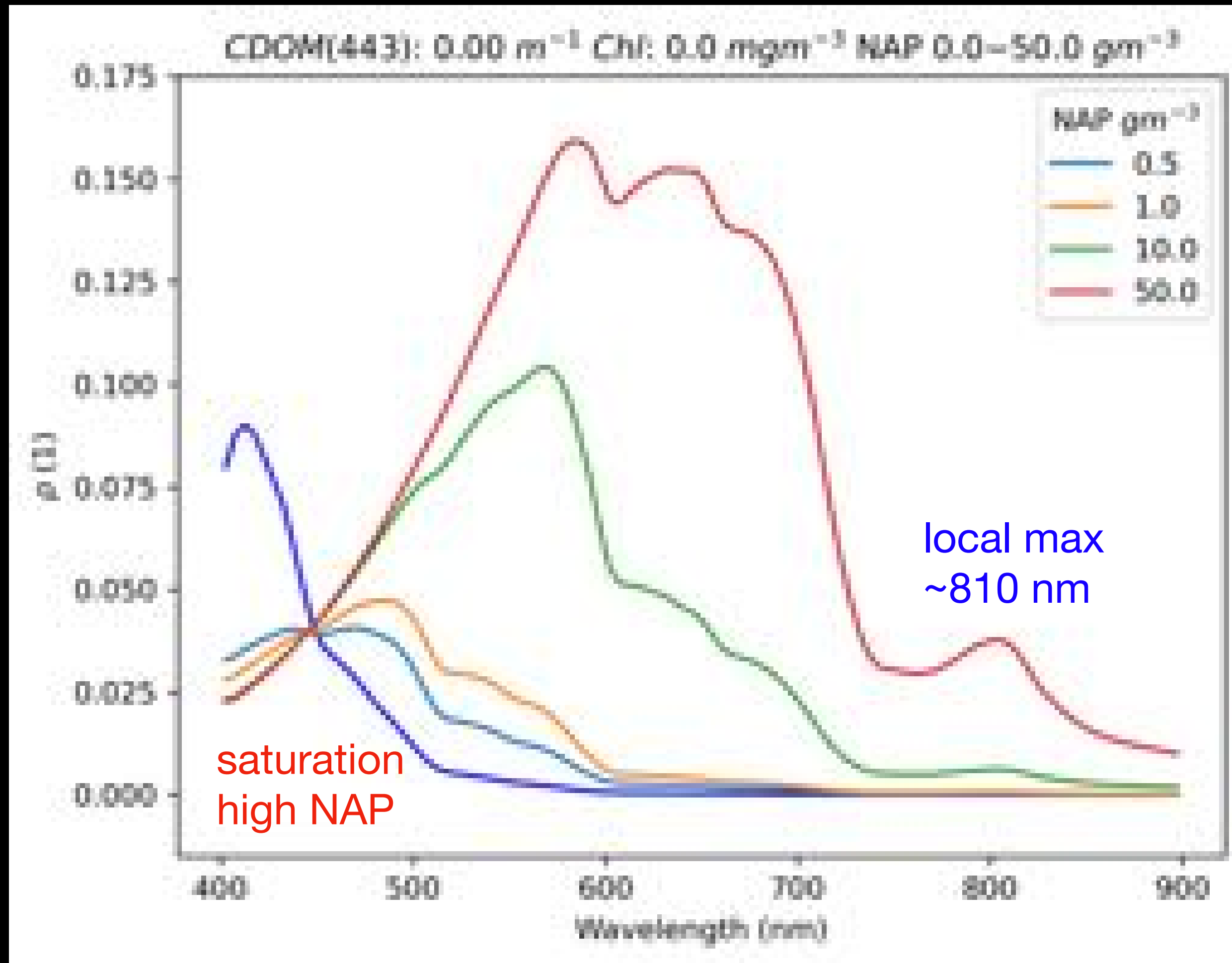
a and b



HYDROLIGHT

$$\rho_w = \pi \times R_{rs}$$

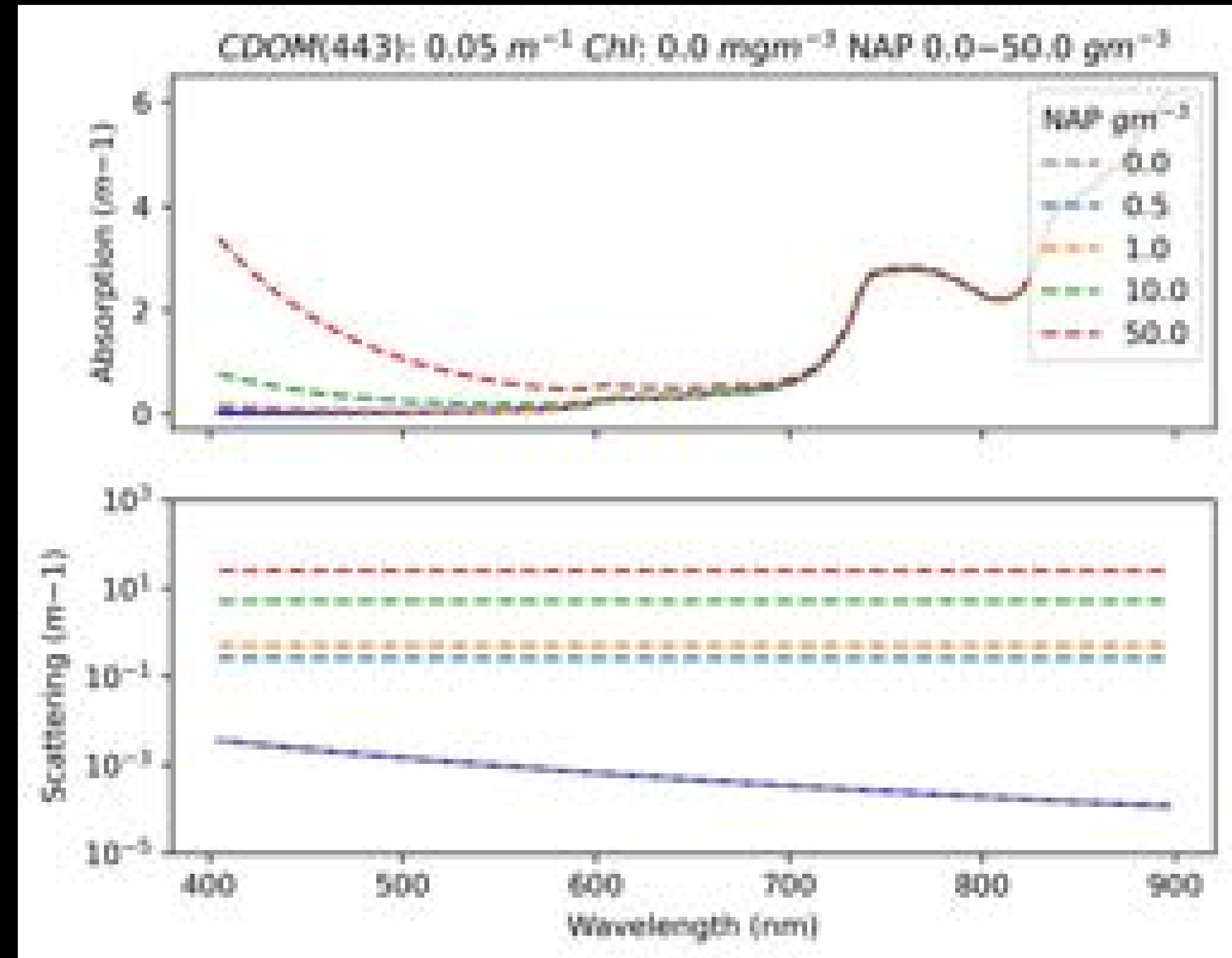
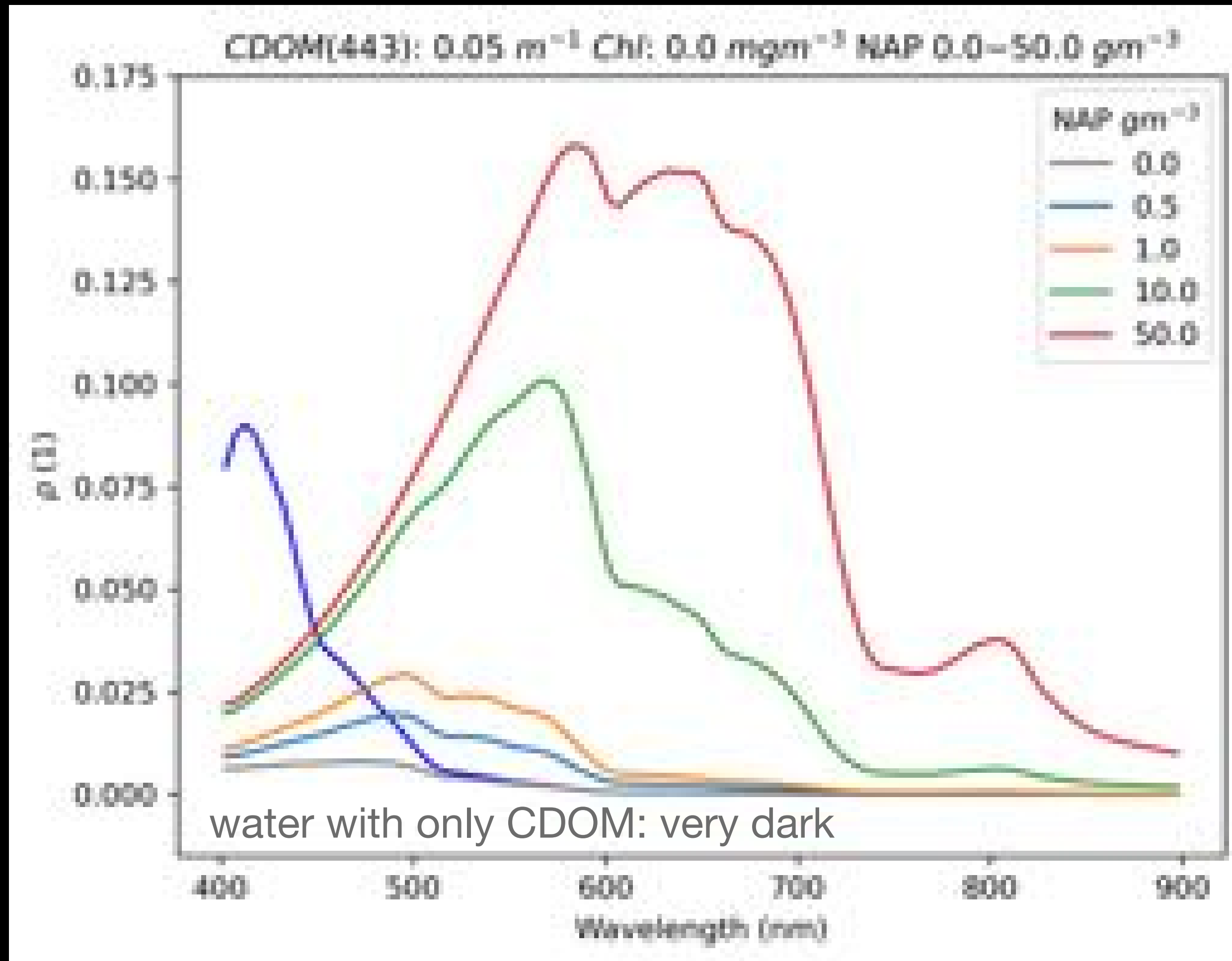
a and b



HYDROLIGHT, NAP range

$$\rho_w = \pi \times R_{rs}$$

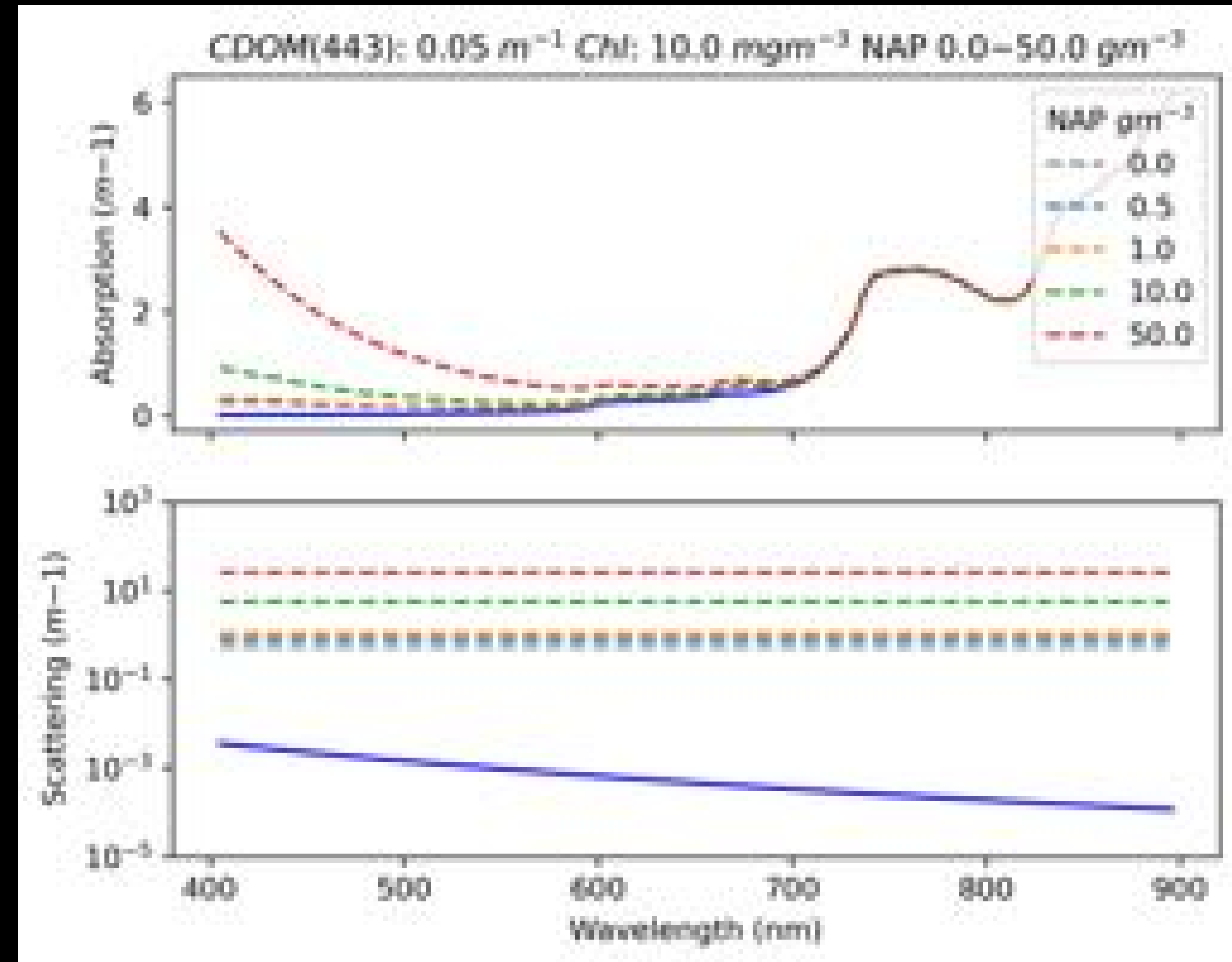
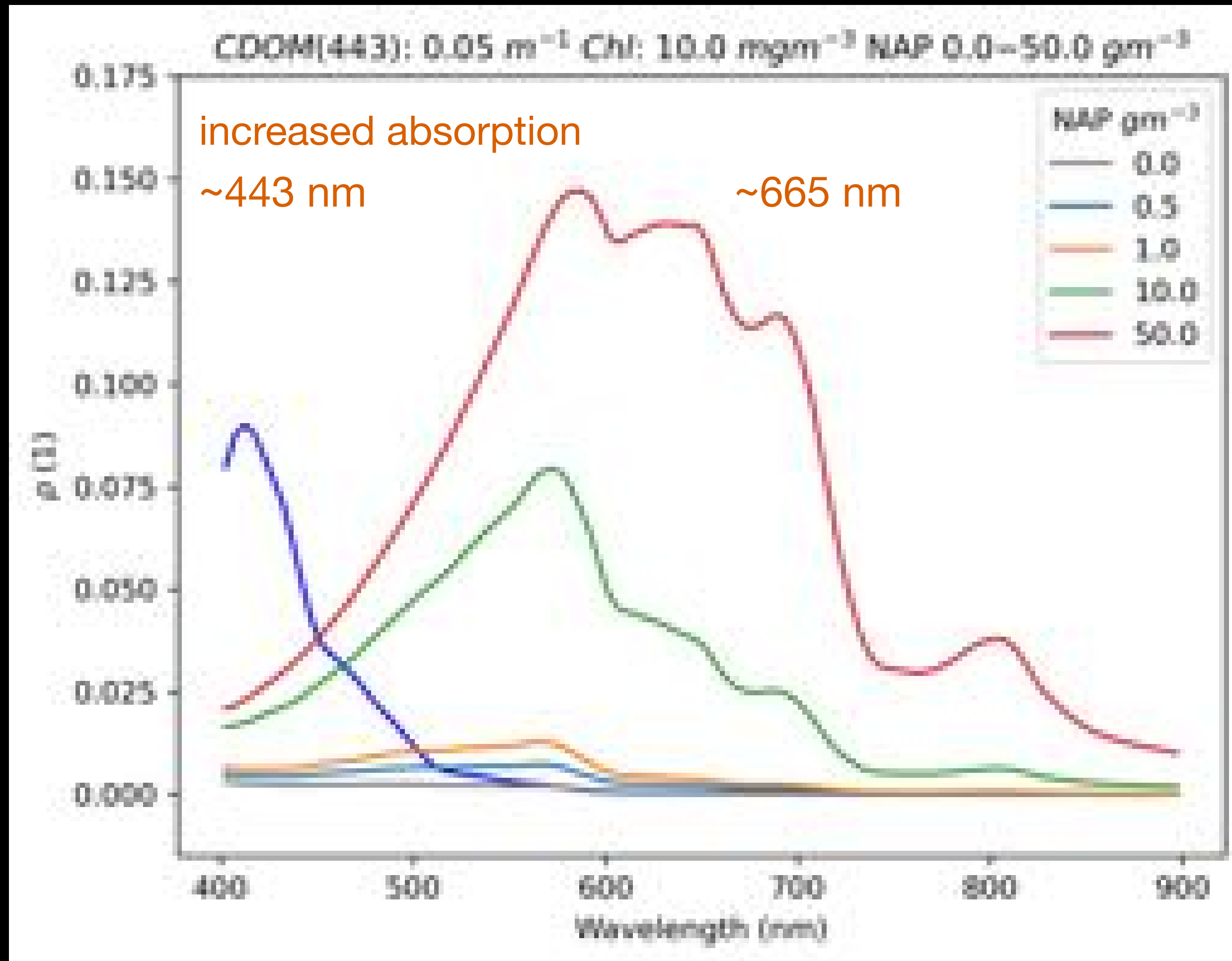
a and b



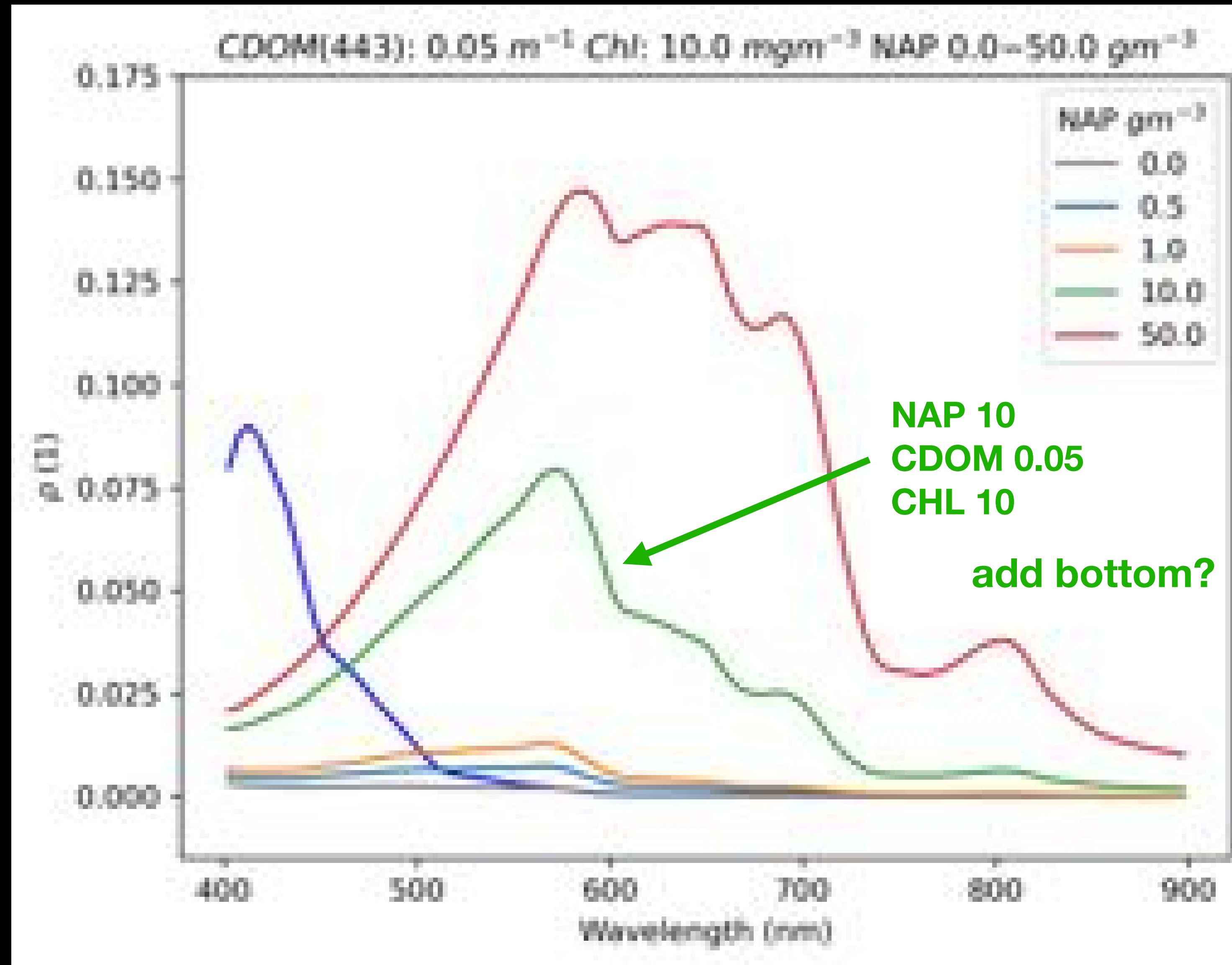
HYDROLIGHT, NAP range, CDOM 0.05

$$\rho_w = \pi \times R_{rs}$$

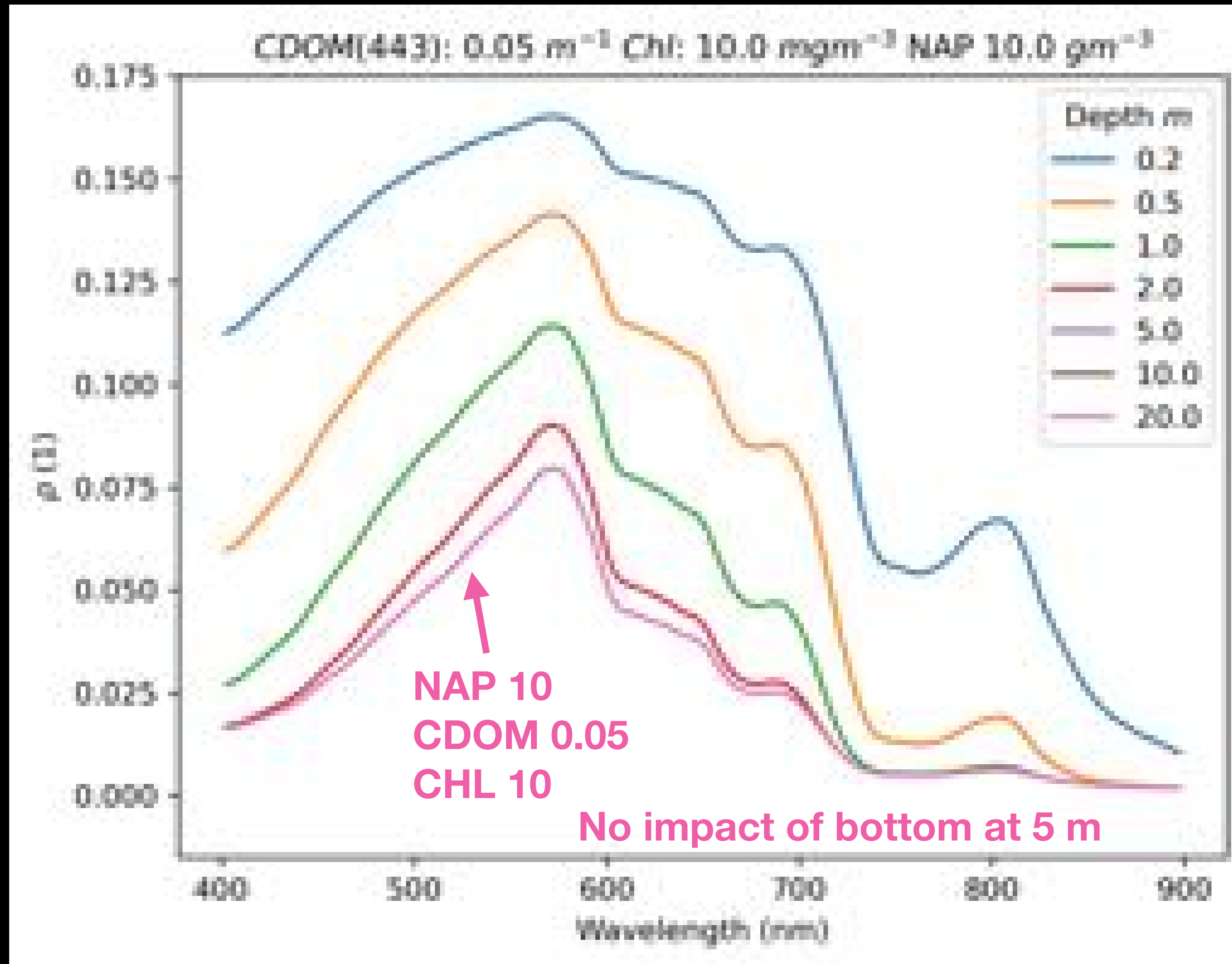
a and b



HYDROLIGHT, NAP range, CDOM 0.05, CHL 10



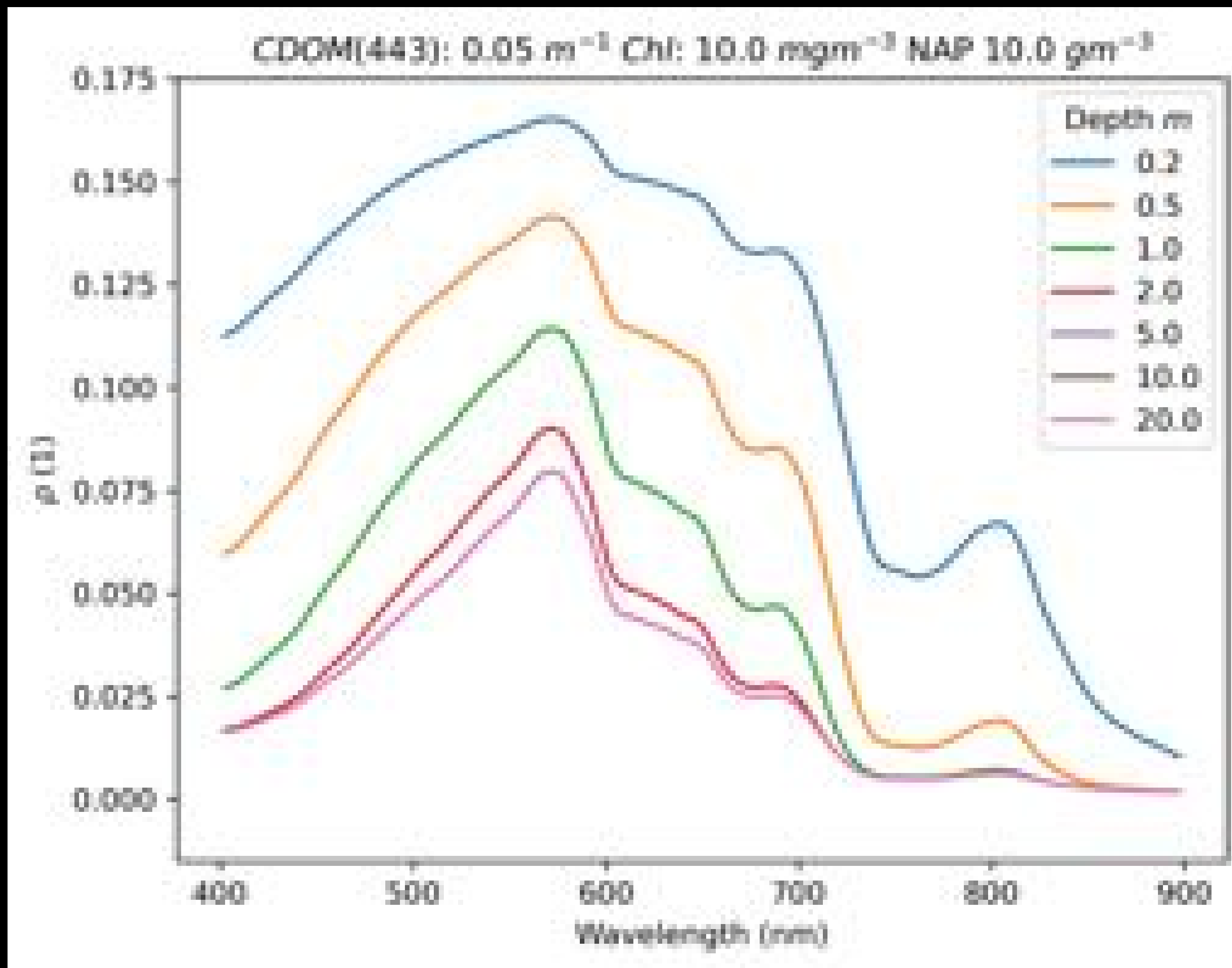
HYDROLIGHT, NAP range, CDOM 0.05, CHL 10



ρ_{bottom} : 0.3

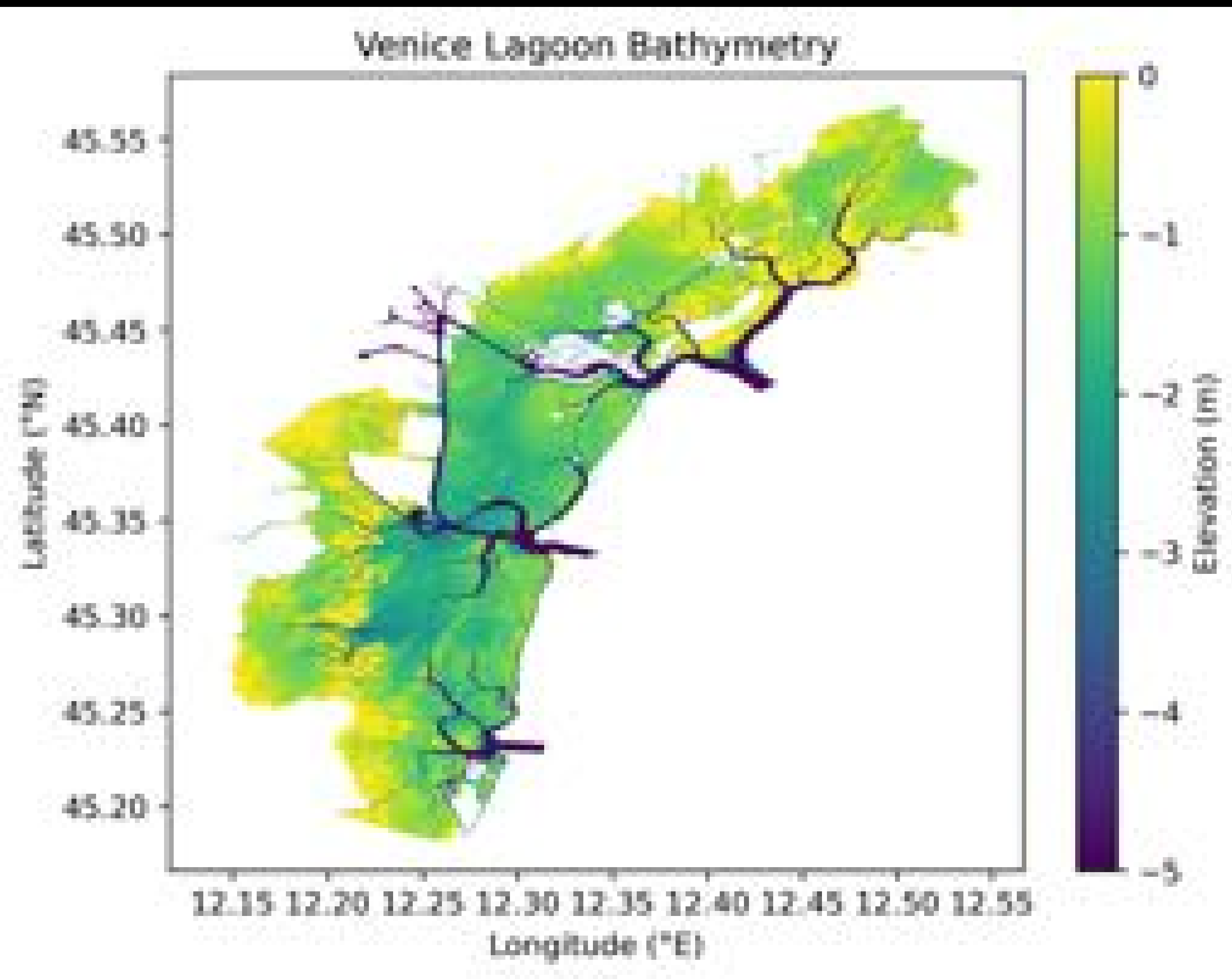
HYDROLIGHT, NAP range, CDOM 0.05, CHL 10, bottom 0.2-20 m

↑
> bottom influence
for shallower depth



ρ_{bottom}: 0.3

HYDROLIGHT, NAP range, CDOM 0.05, CHL 10, bottom 0.2-20 m



~7% > 5 m depth

~82% < 2 m depth

~43% < 1 m depth

~15% < 0.5 m depth

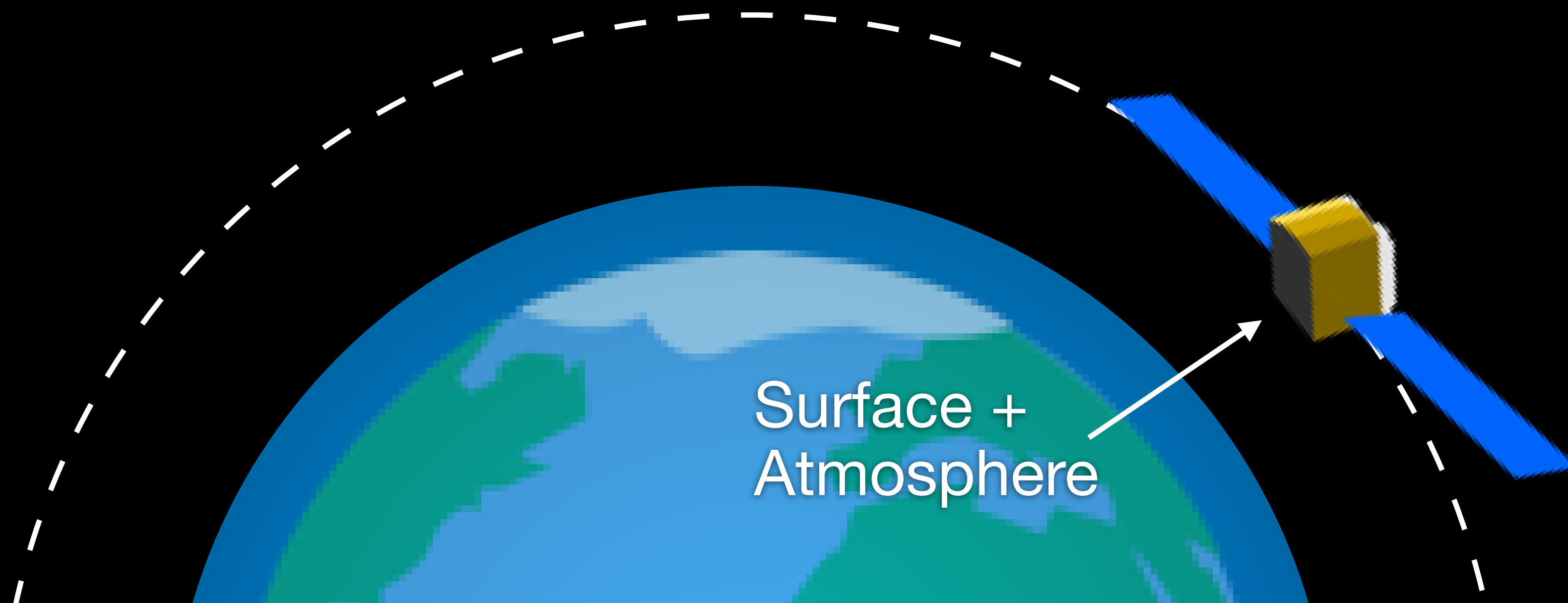
Issues with atmospheric correction

Atmospheric correction algorithms are complex, and assumptions and limitations are not always obvious

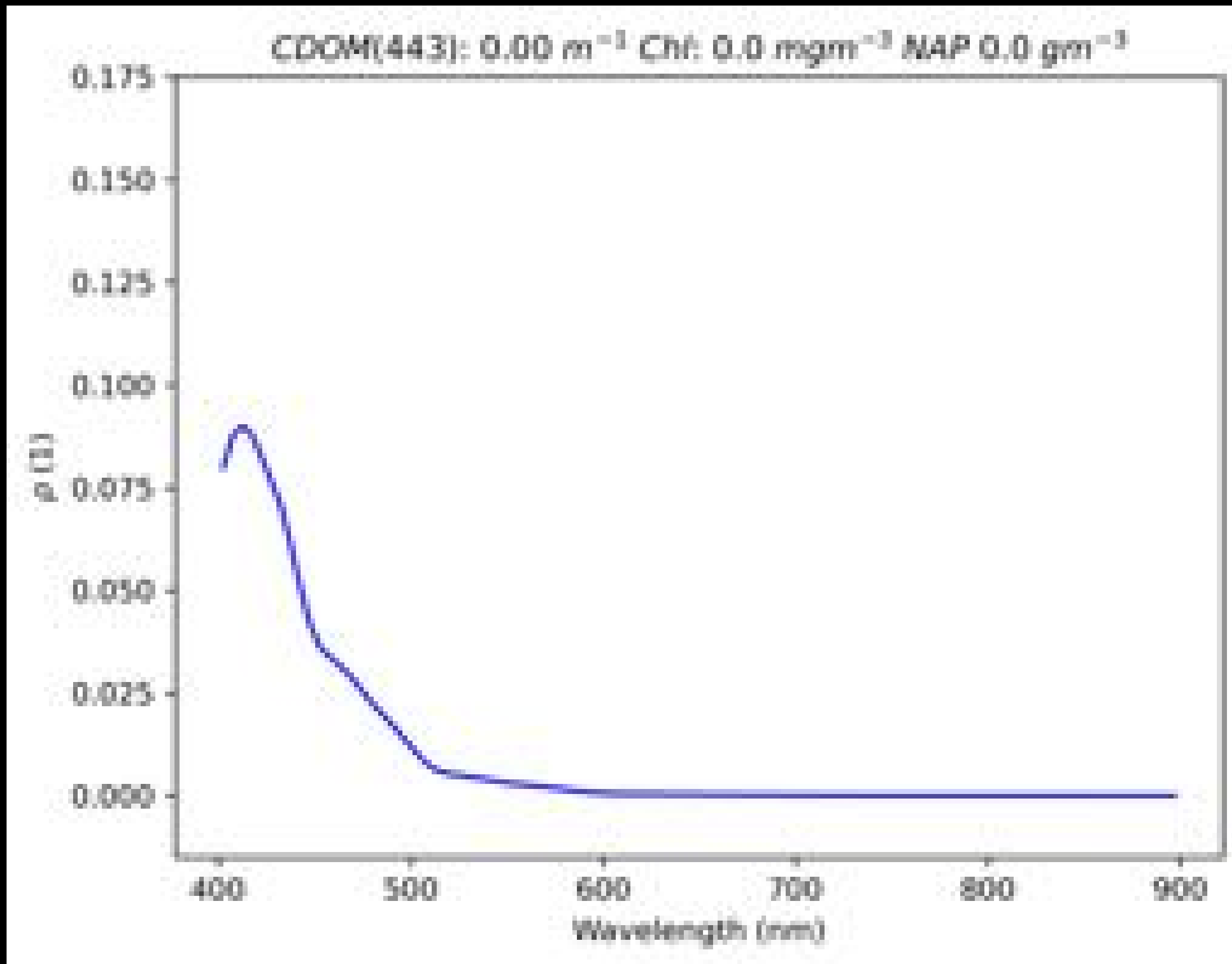
Atmospheric correction

Need for atmospheric correction:

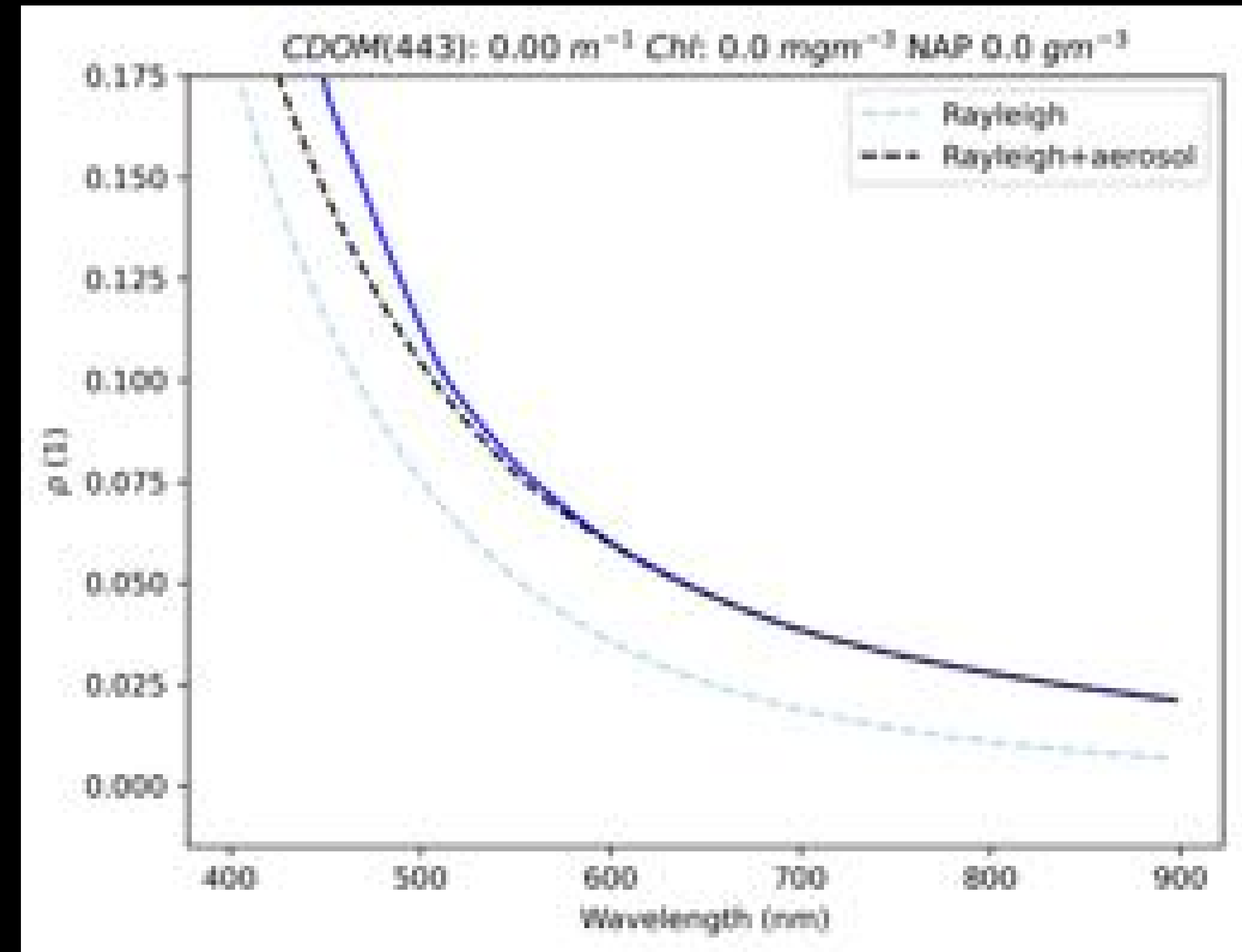
- **remote observation combines the signals from the target, the atmosphere, and the interface between target and atmosphere**
- **for near surface sensors the effect of atmosphere between the sensor and the target is minimal, but for airborne, or top-of-atmosphere (TOA) sensors the atmosphere can dominate the signal**



$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$

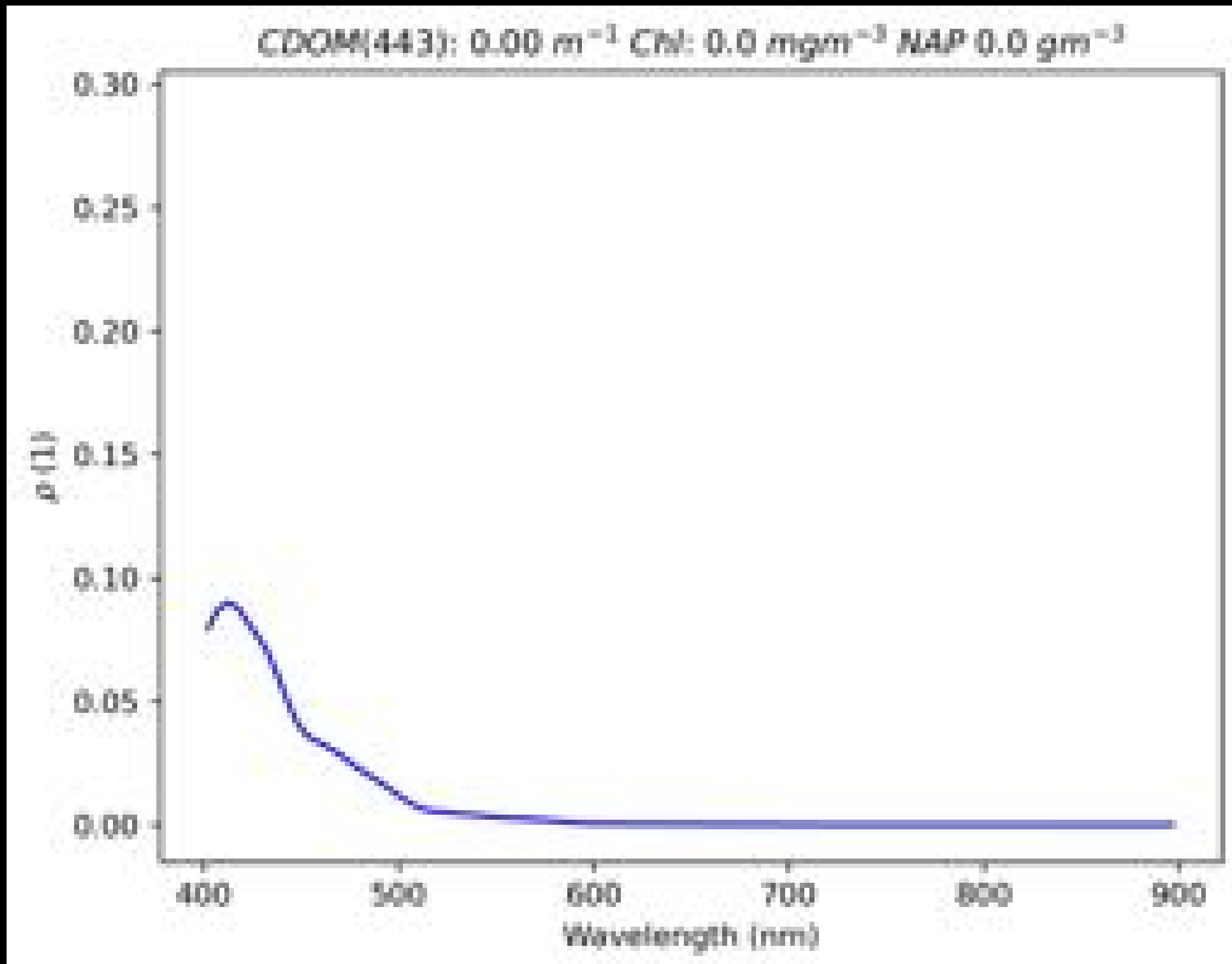


BOA

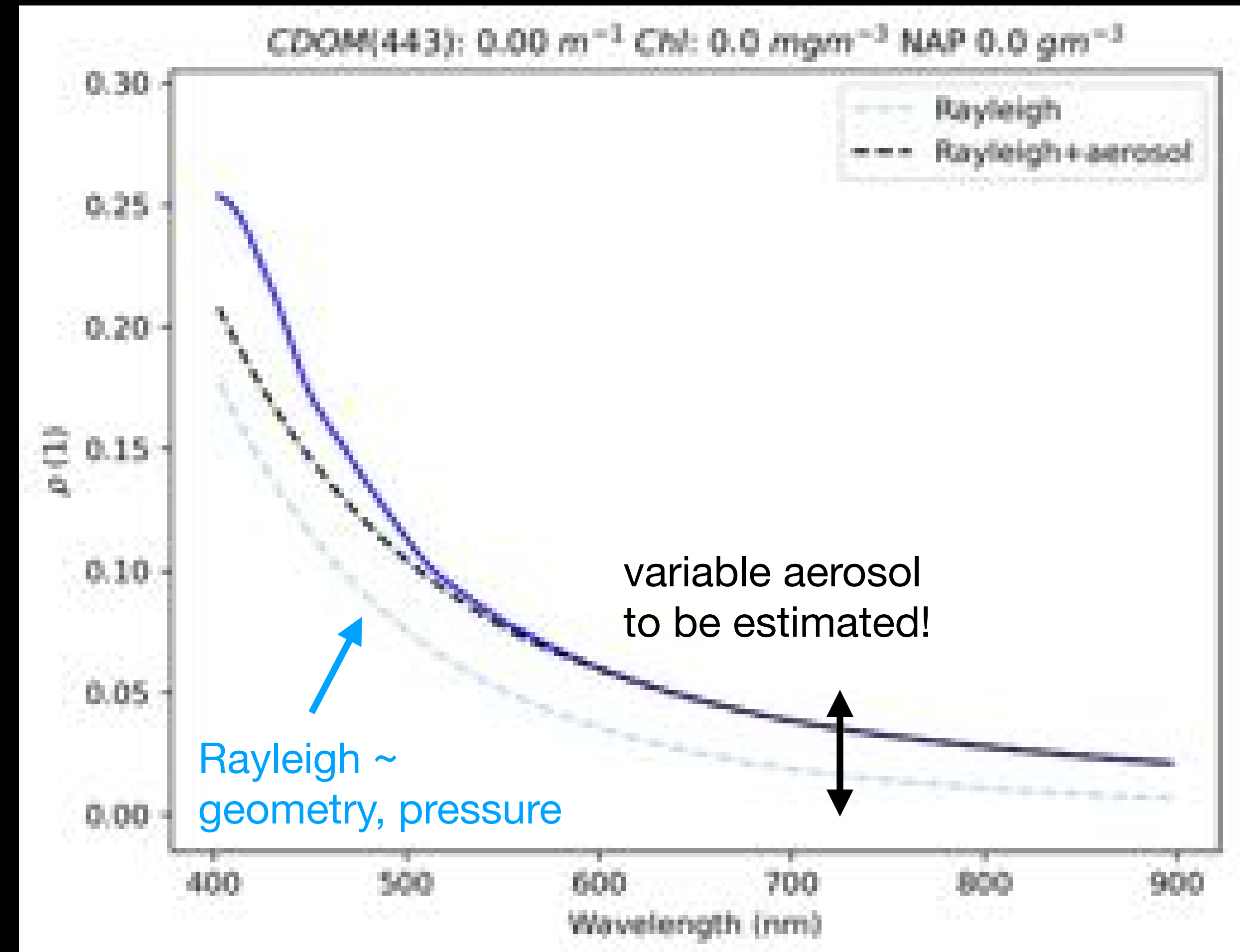


TOA

$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$



BOA

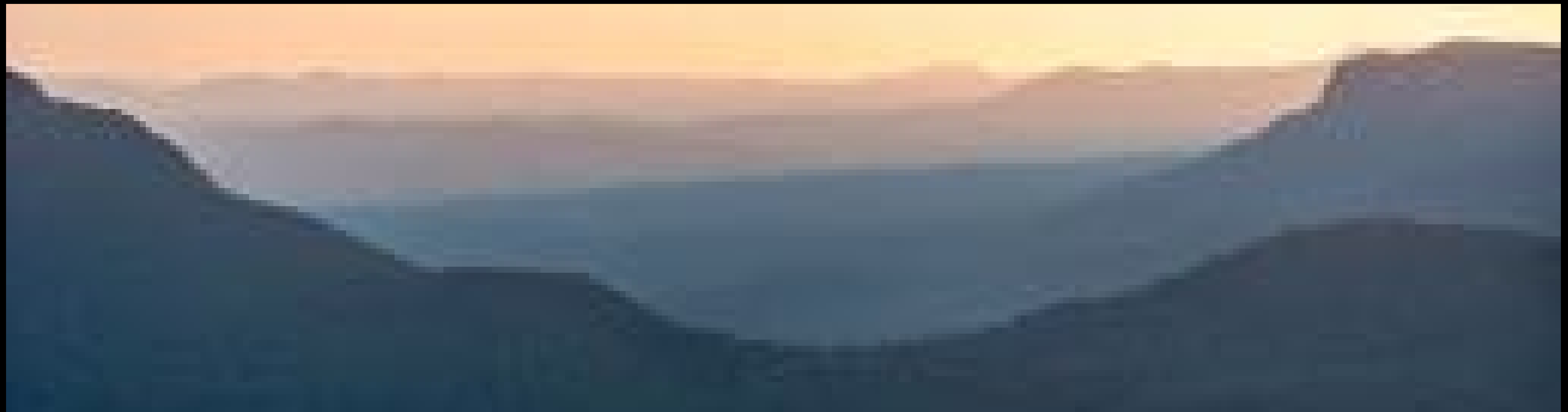


TOA

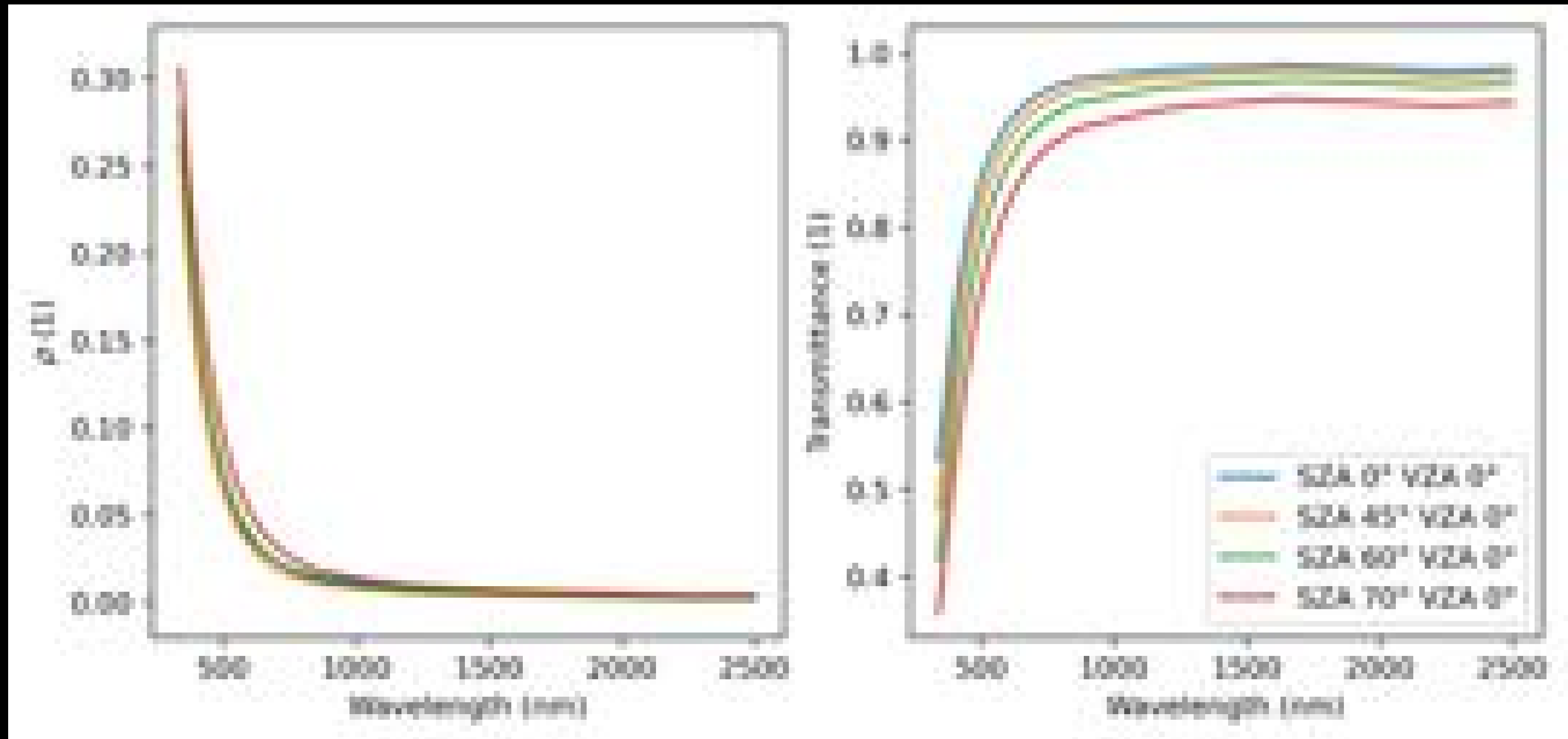
Atmospheric correction

Need for atmospheric correction:

- the atmospheric path reflectance and transmittance varies with illumination and observation geometry, scaling with atmospheric path length, simplified as $1/\cos(vza) + 1/\cos(sza)$
- the extraterrestrial solar irradiance (F_0) varies throughout the year with the sun-earth distance (d), and is scaled from reference irradiance value by d^2

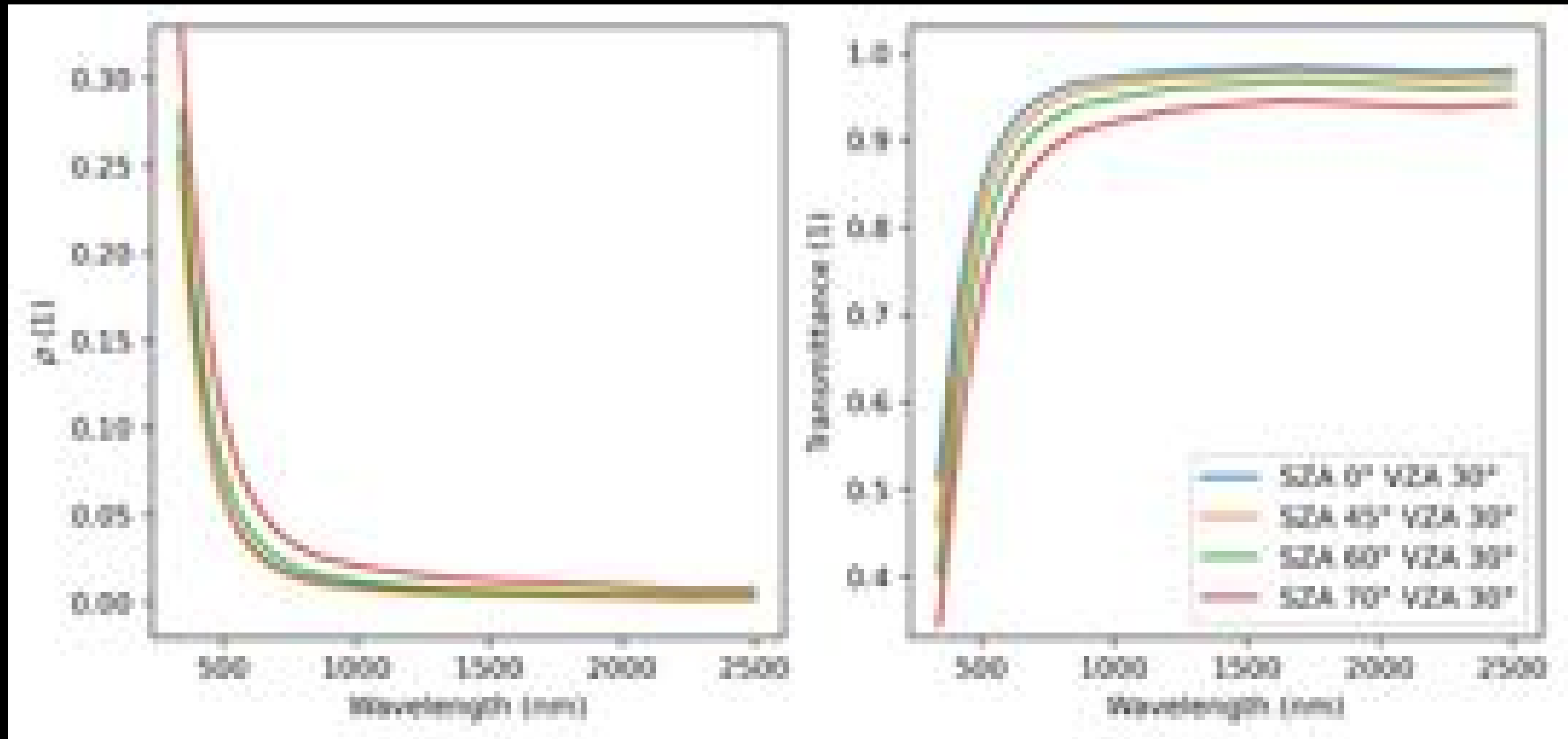


Path reflectance and transmittance



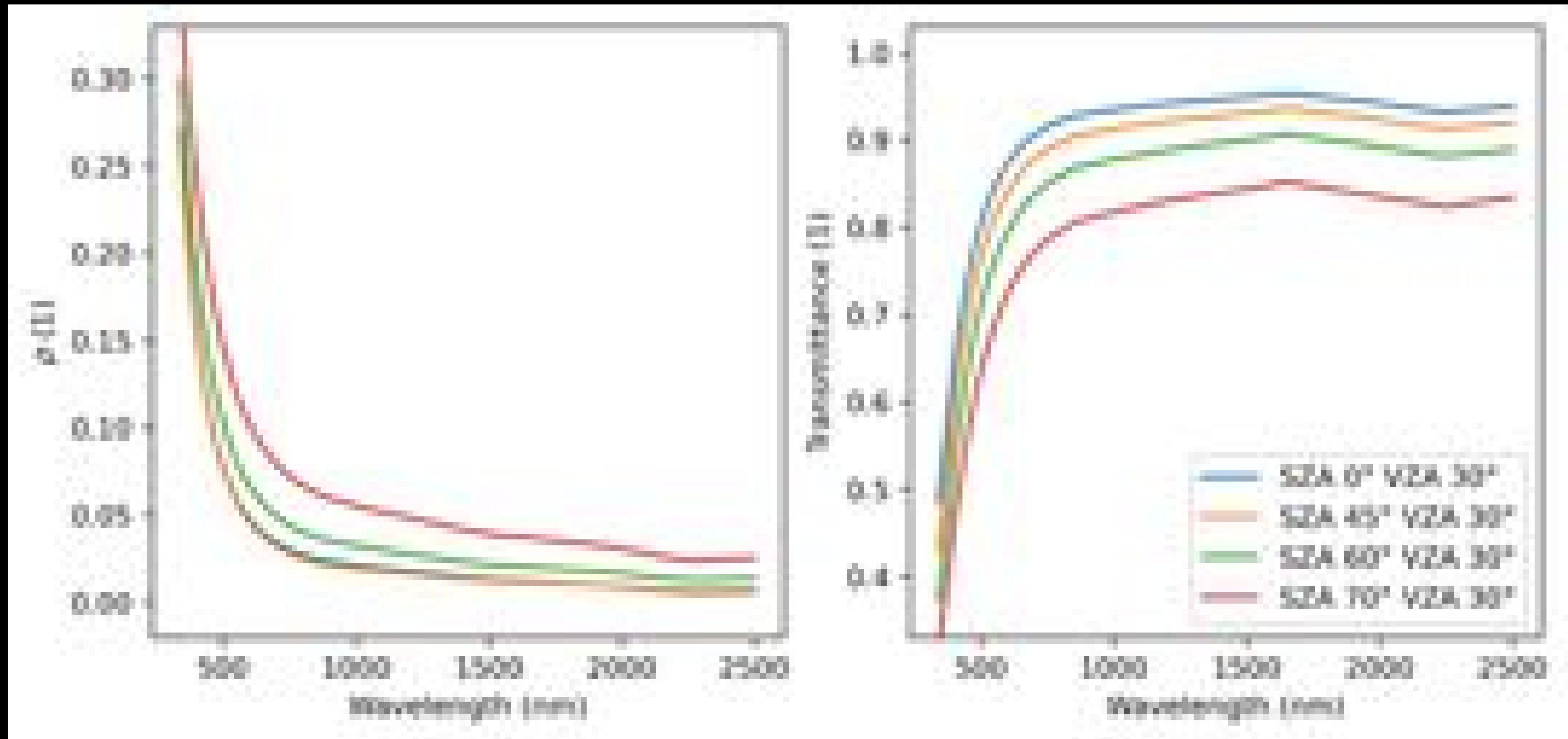
6SV model, τ_a 550 nm 0.1, maritime aerosol

Path reflectance and transmittance



6SV model, τ_a 550 nm 0.1, maritime aerosol

Path reflectance and transmittance



6SV model, τ_a 550 nm 0.3, maritime aerosol

Atmospheric correction

Required for atmospheric correction:

- absorption by atmospheric gases (O₃, H₂O, but many others) ~ concentration, geometry
- scattering and absorption by air molecules (Rayleigh) ~ air pressure, geometry
- scattering and absorption by particles (aerosol) ~ particle type and concentration, geometry
- air-water interface: sky and sun glint, whitecaps, foam ~ wind speed, geometry

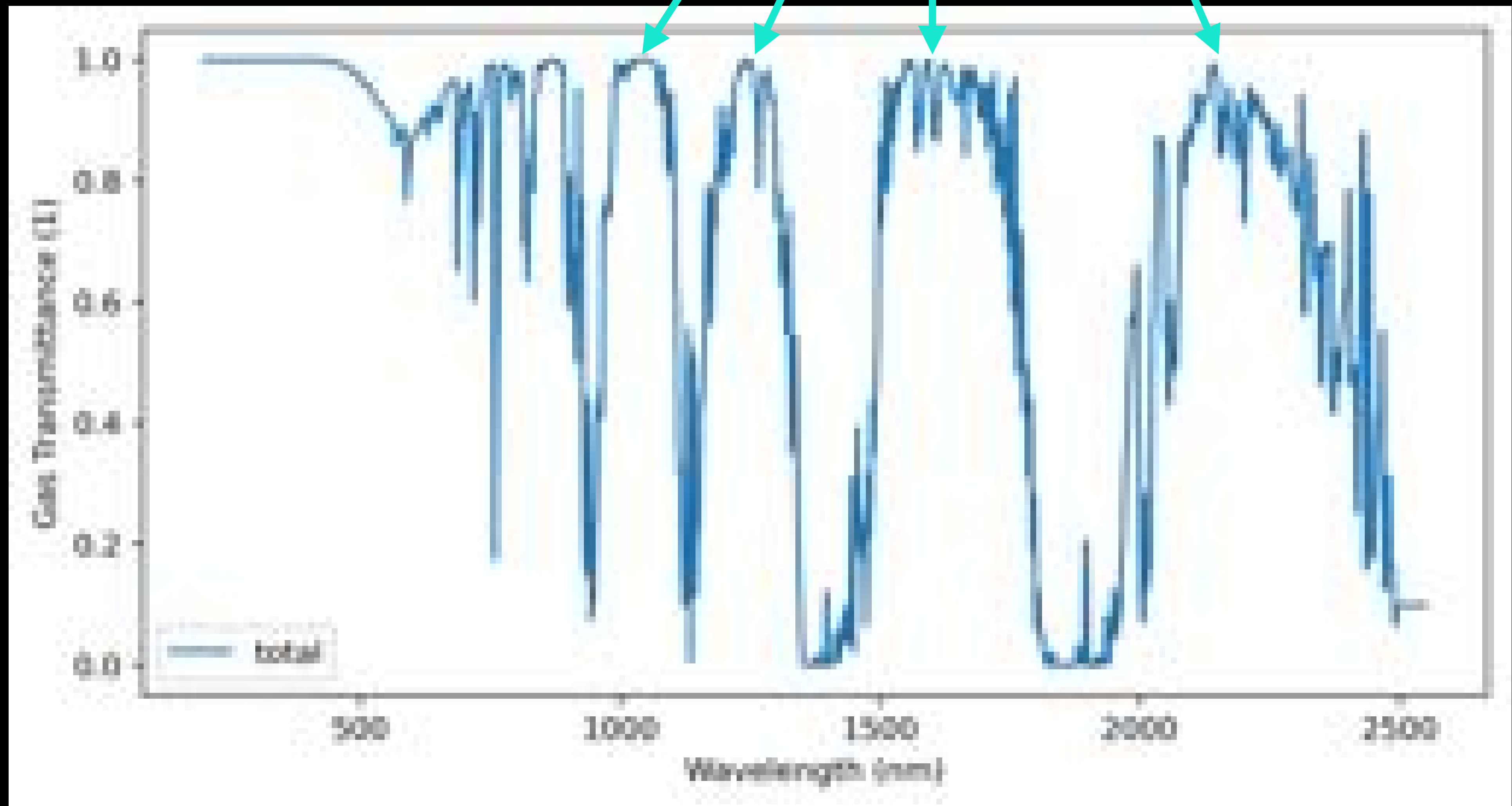
Pressure, wind speed, atmospheric gas concentration

- ancillary data, global climatologies or reasonable defaults

Aerosol information

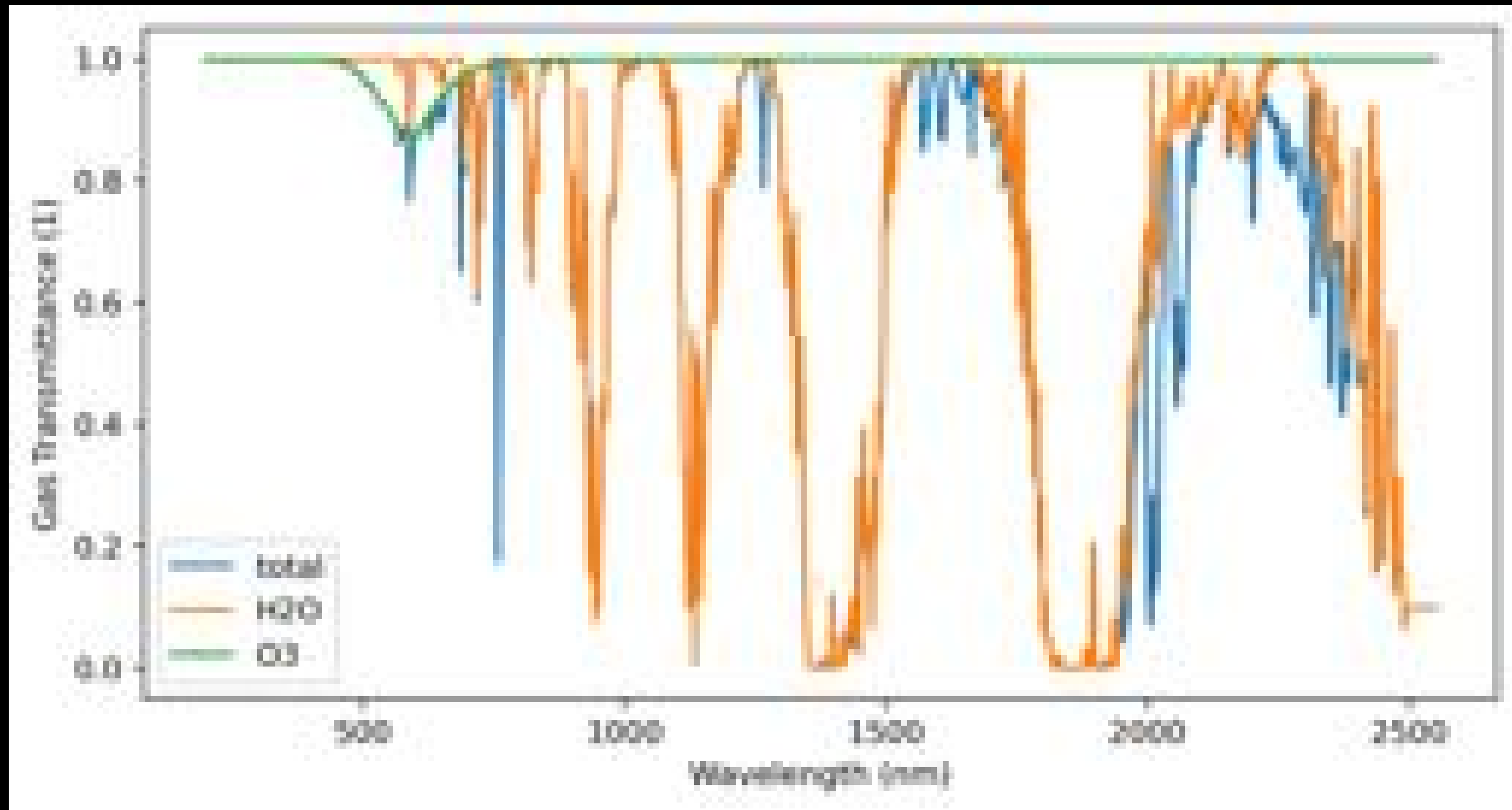
- from ancillary data or measurements (uncommon)
- estimated from the image, either directly or indirectly

Gas transmittance



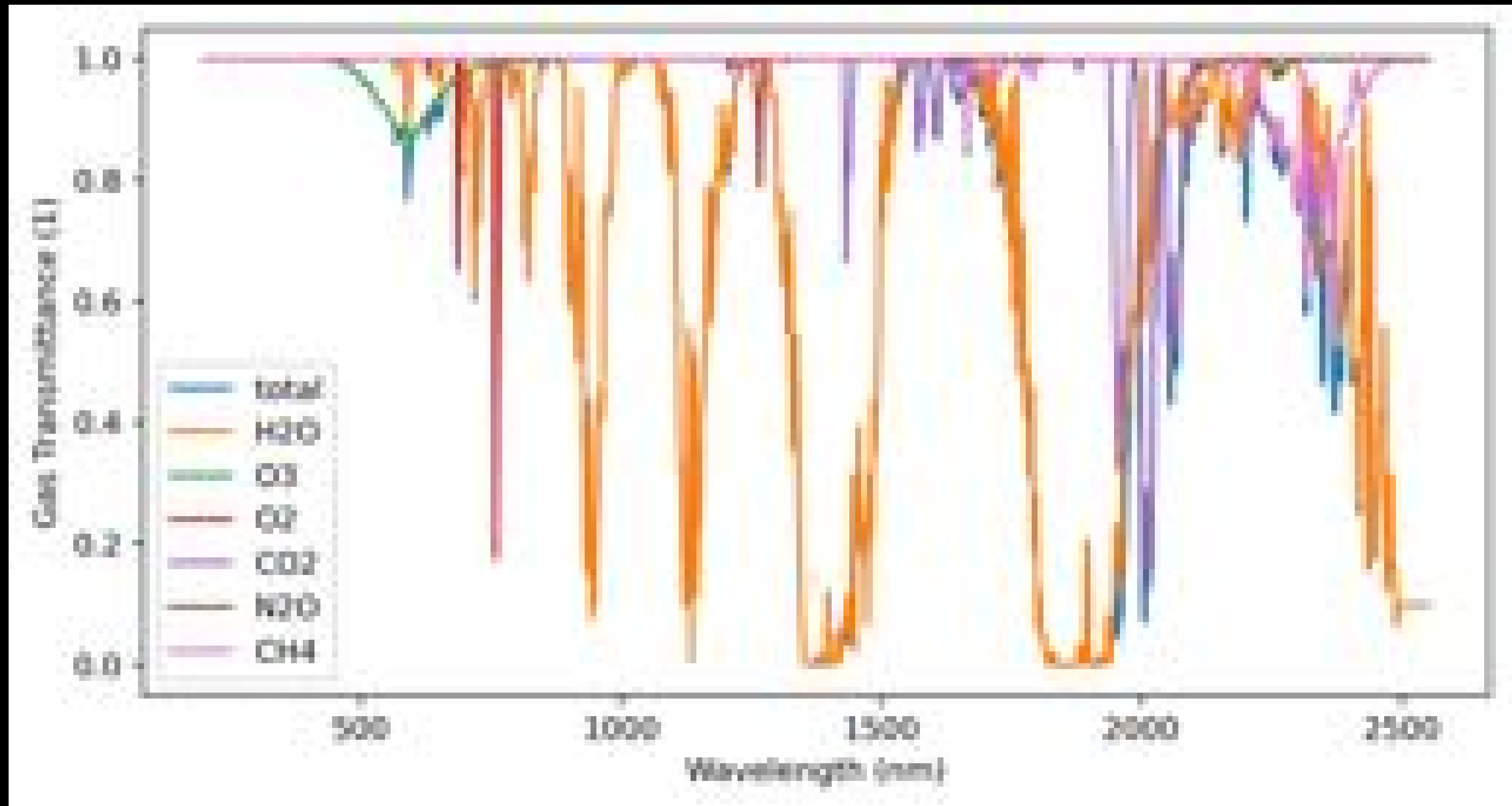
6SV model, 2.5 nm, θ_s 60°, θ_v 40°, ozone 0.3 cm-atm, water 1.5 g/cm²

Gas transmittance



6SV model, 2.5 nm, θ_s 60°, θ_v 40°, ozone 0.3 cm-atm, water 1.5 g/cm²

Gas transmittance

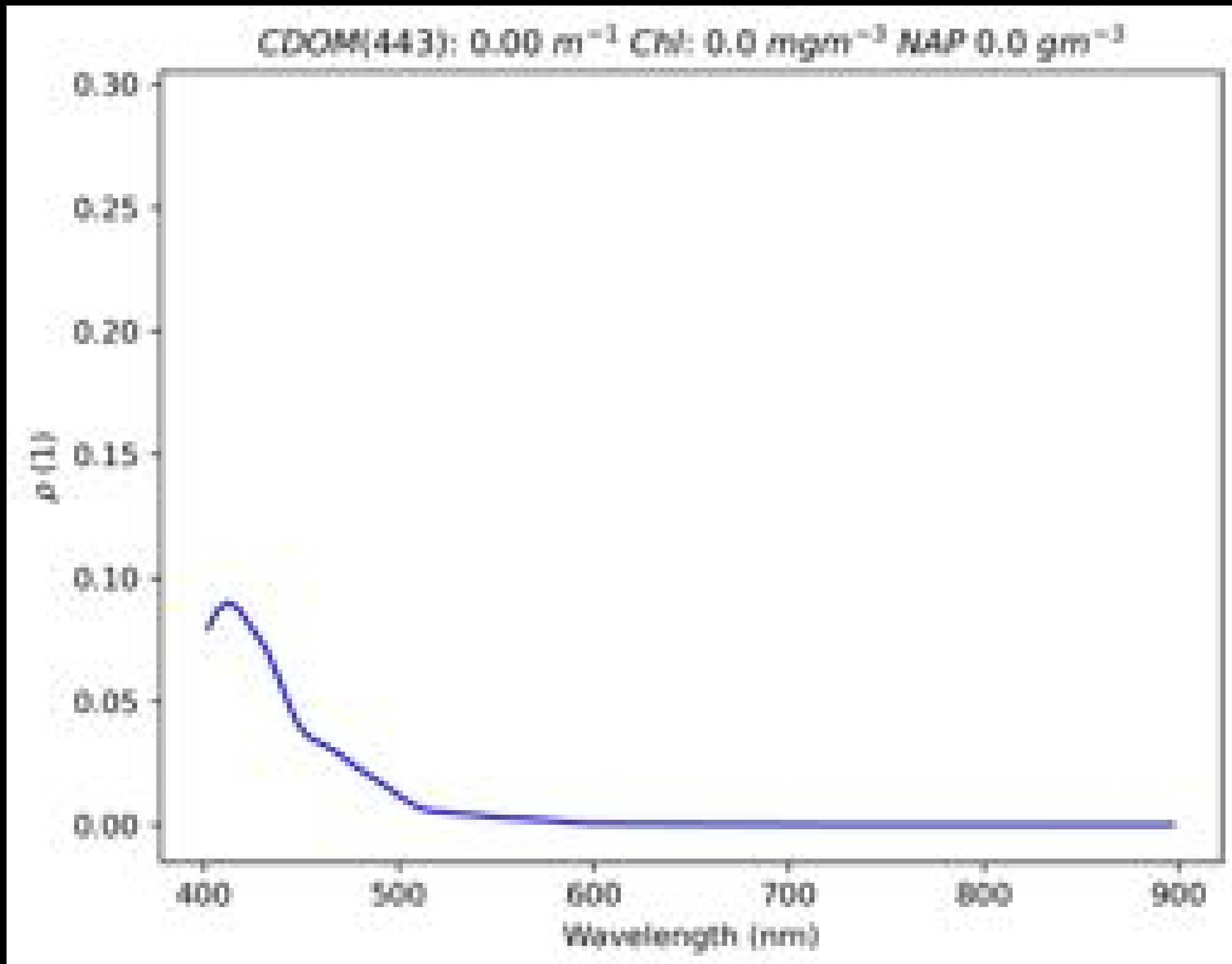


6SV model, 2.5 nm, θ_s 60°, θ_v 40°, ozone 0.3 cm-atm, water 1.5 g/cm²

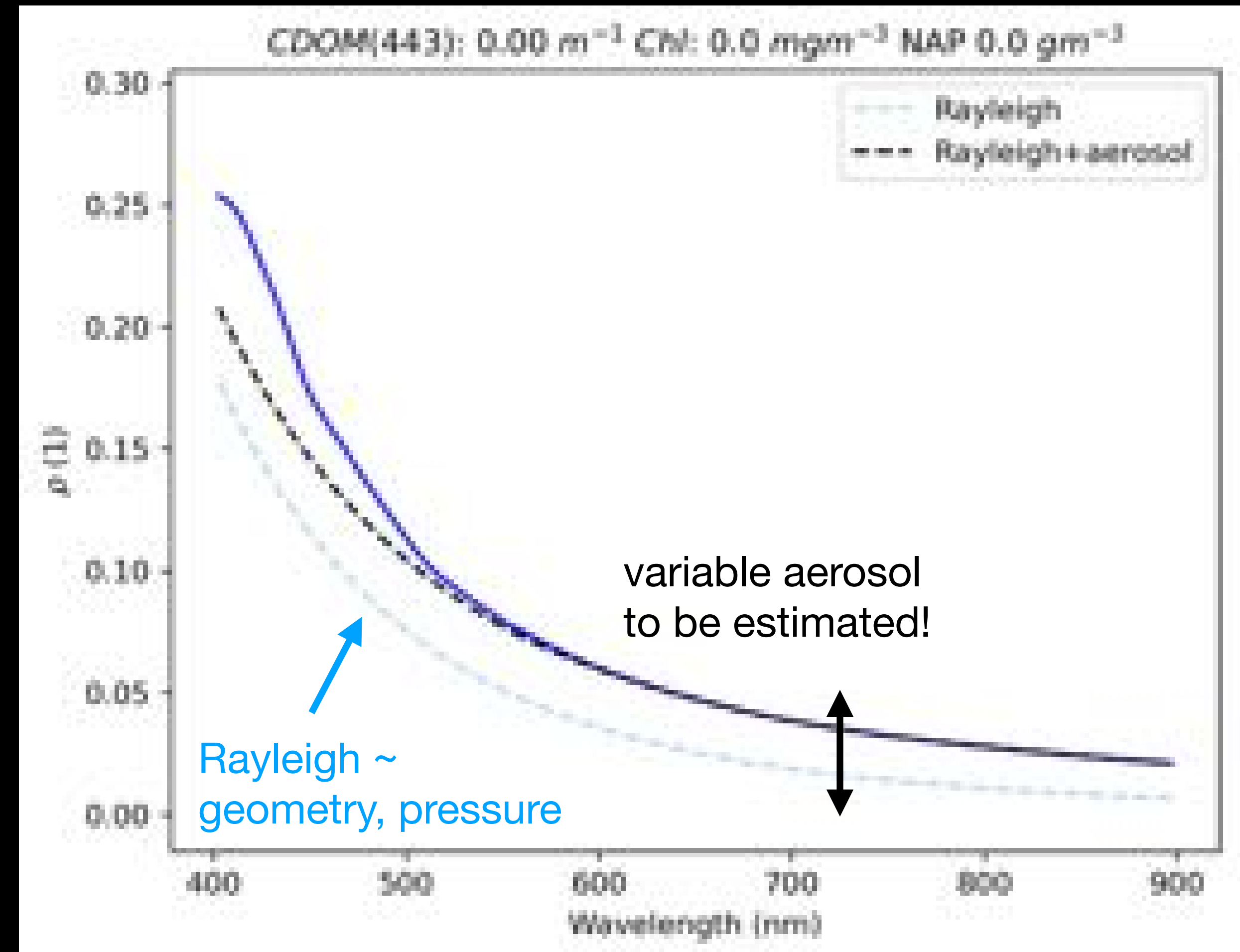
Aerosol estimation

- 1) Traditional ocean colour approach ~ dark NIR over water
 - SeaDAS/l2gen, NASA/NOAA, Gordon and Wang (1994)
 - ESA MERIS/OLCI, Antoine et al. (1997)

$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$

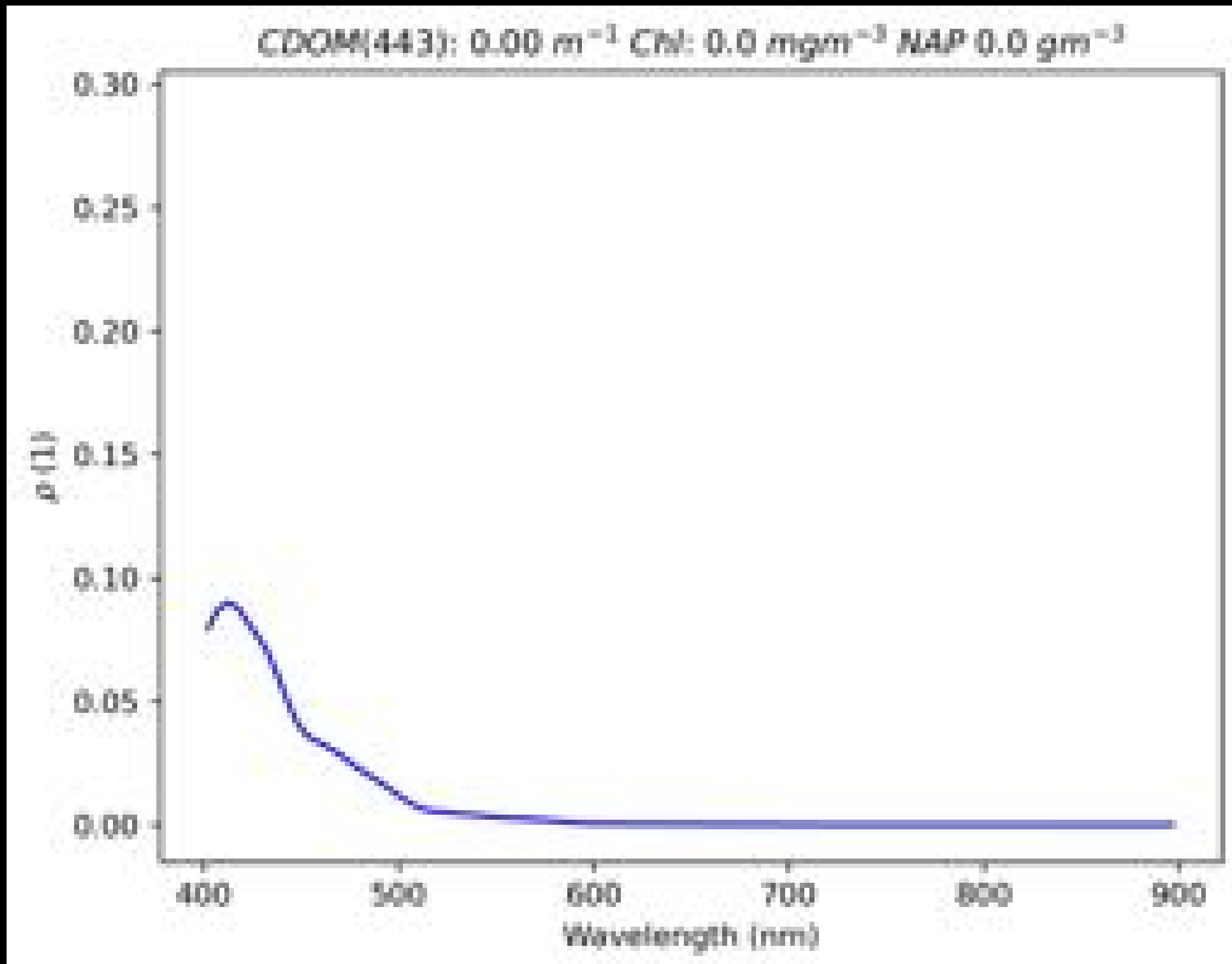


BOA

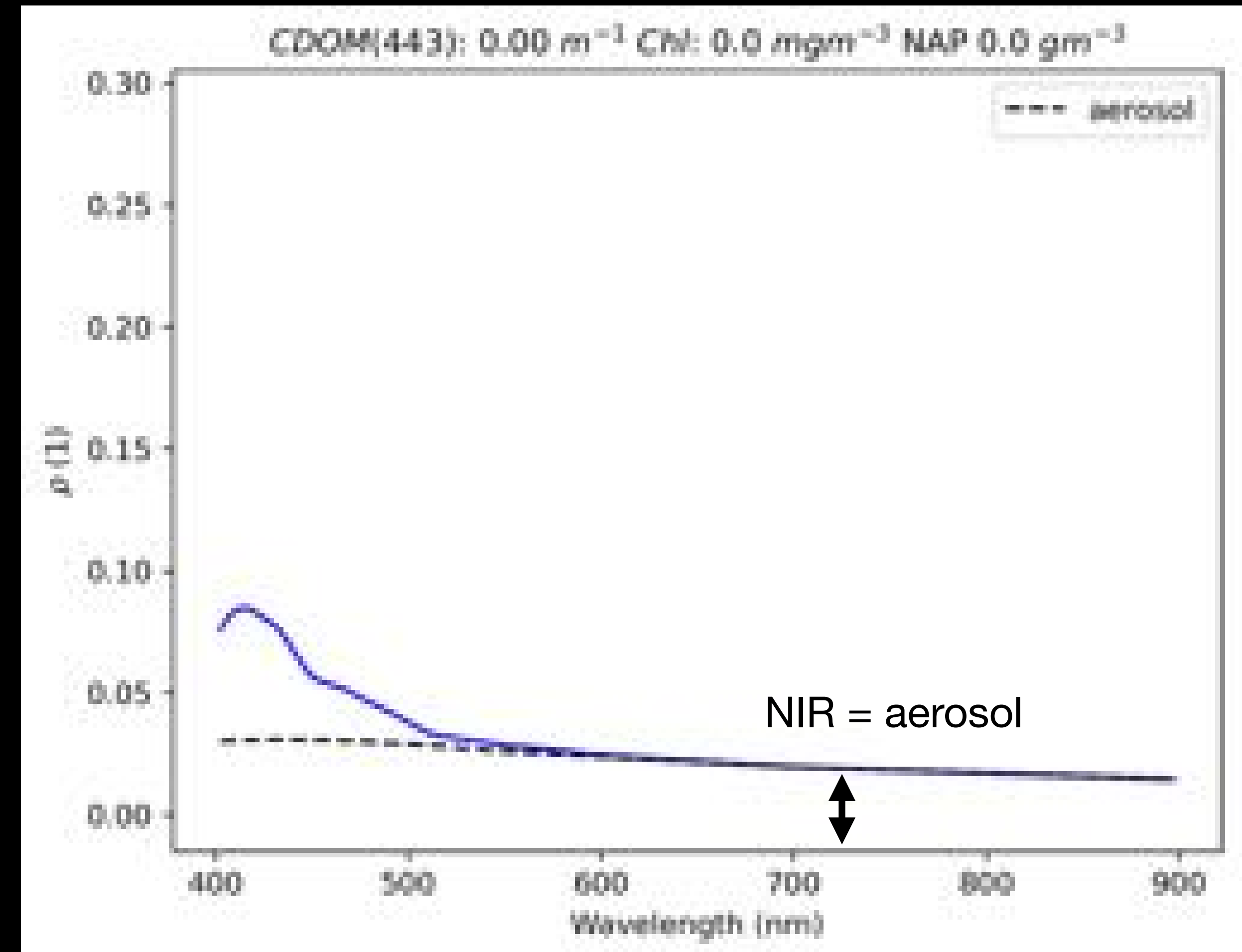


TOA

$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$

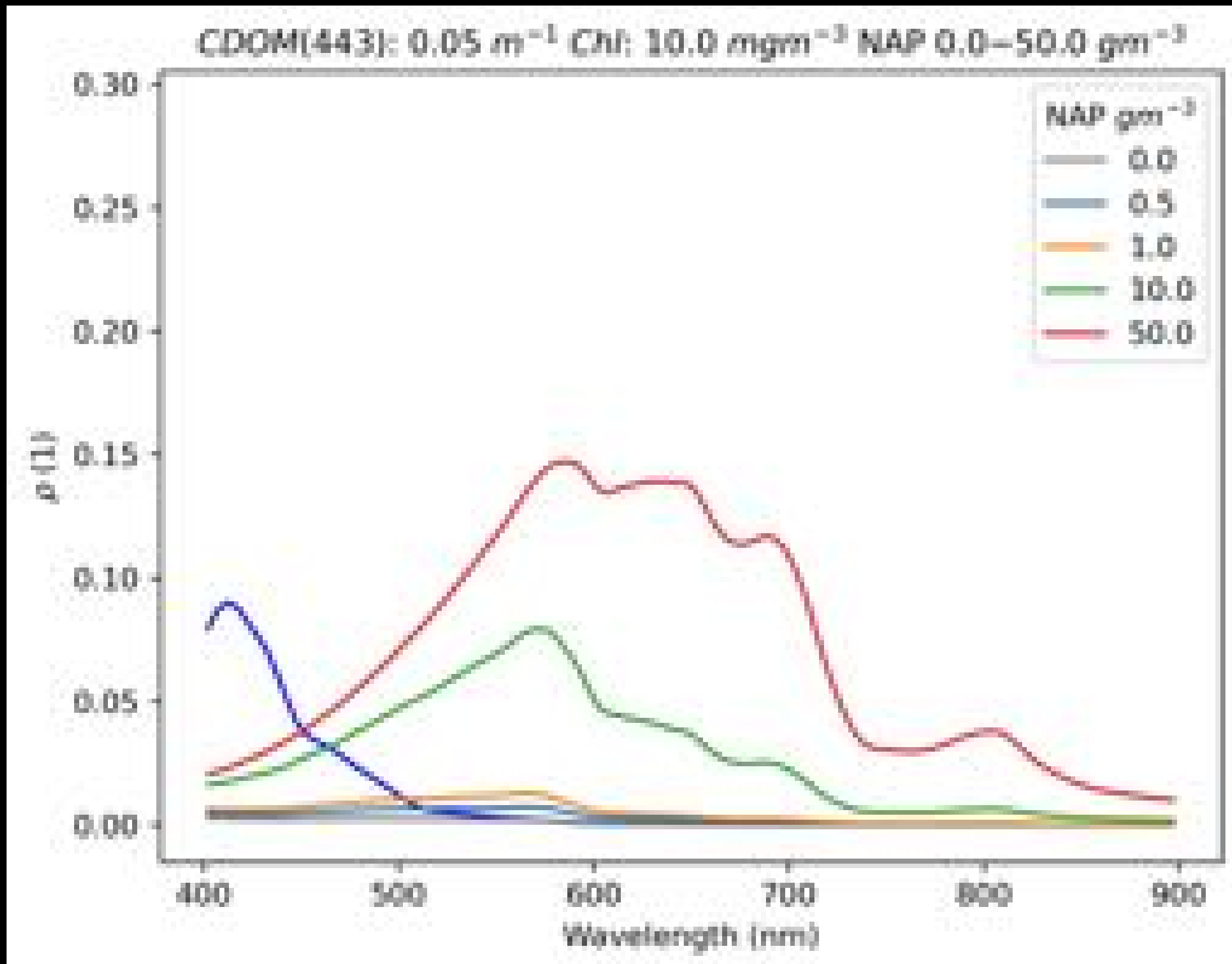


BOA

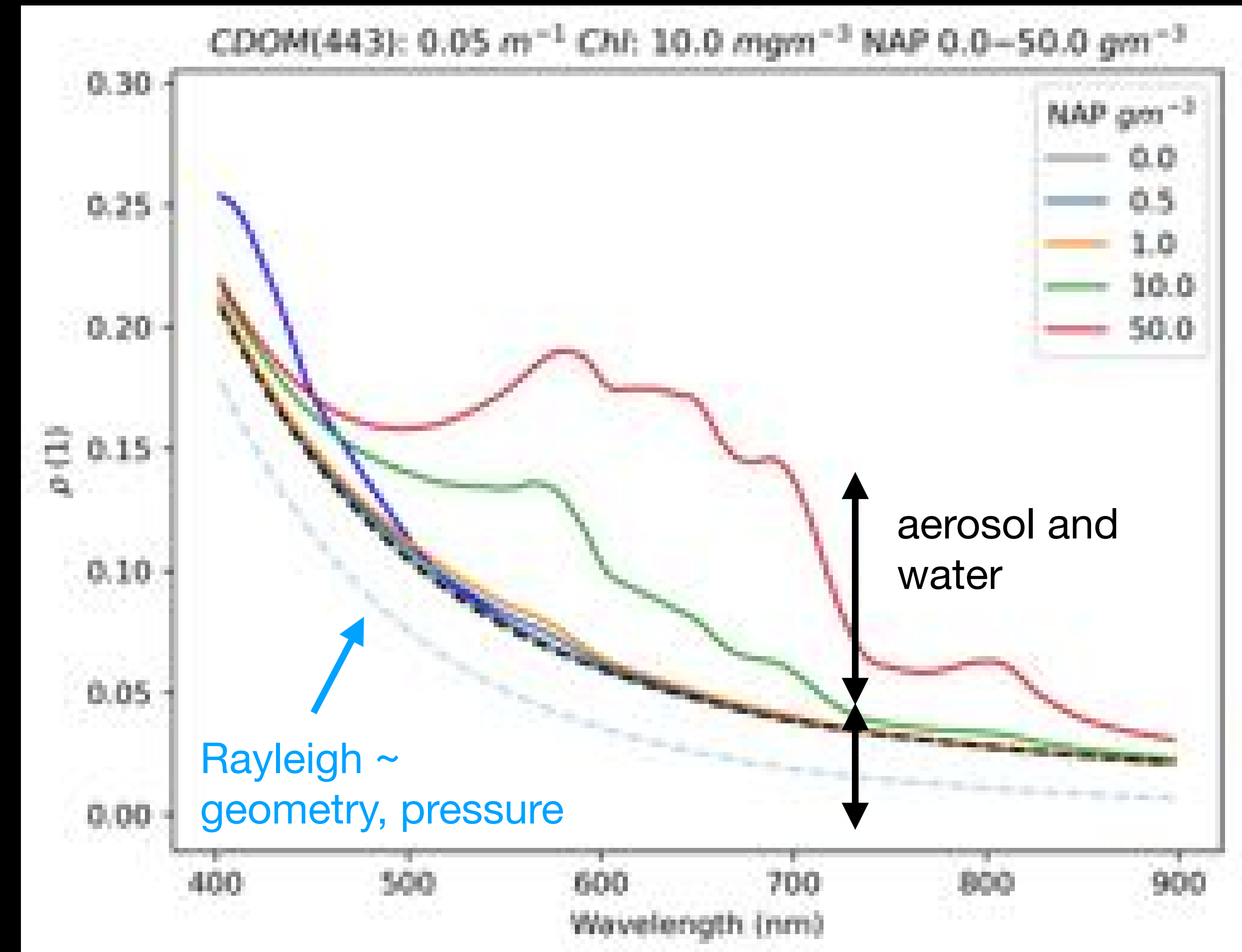


TOA-Rayleigh

$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$

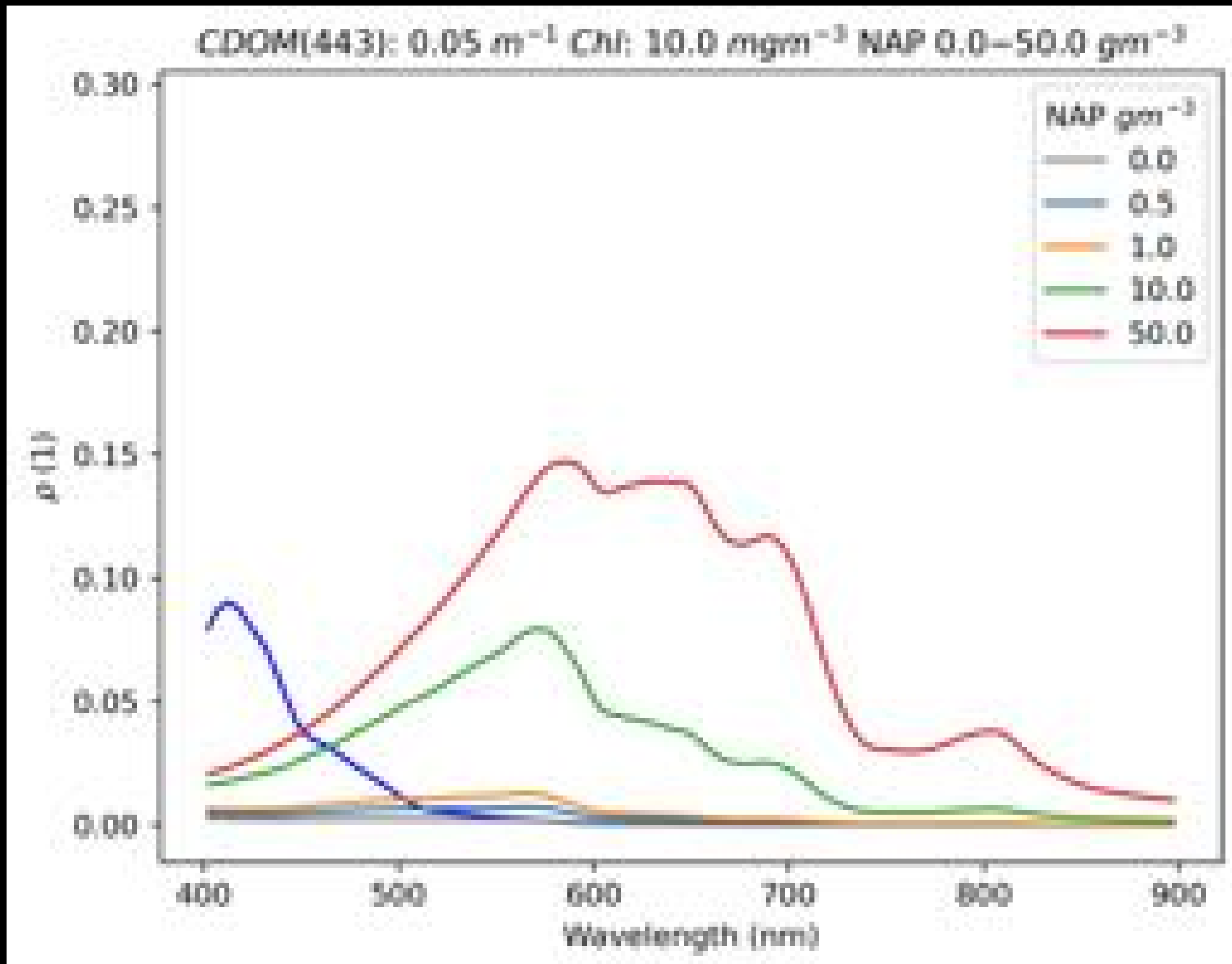


BOA

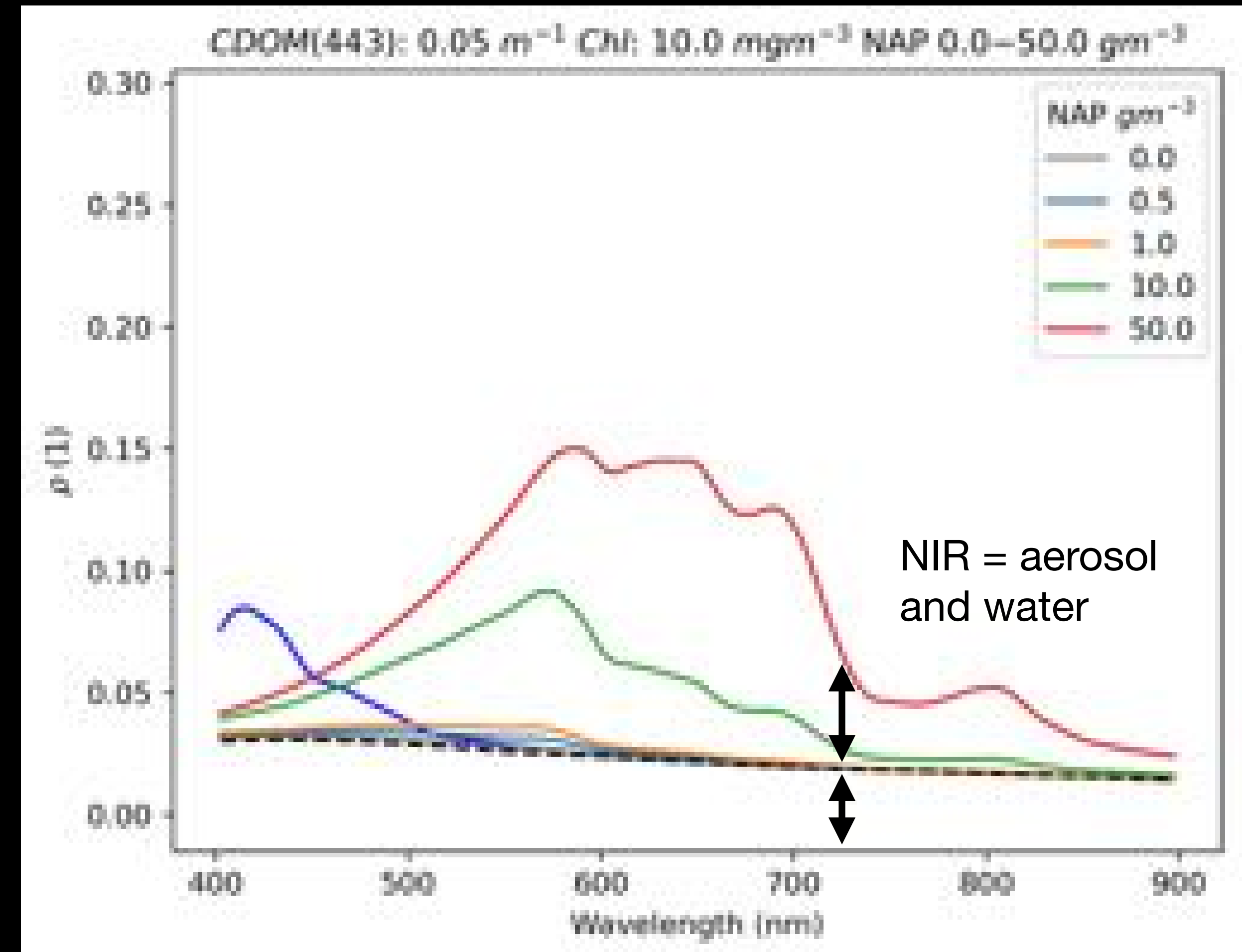


TOA

$\theta_s 60^\circ \theta_v 40^\circ \tau_a 550 \text{ nm} = 0.1$



BOA



TOA-Rayleigh

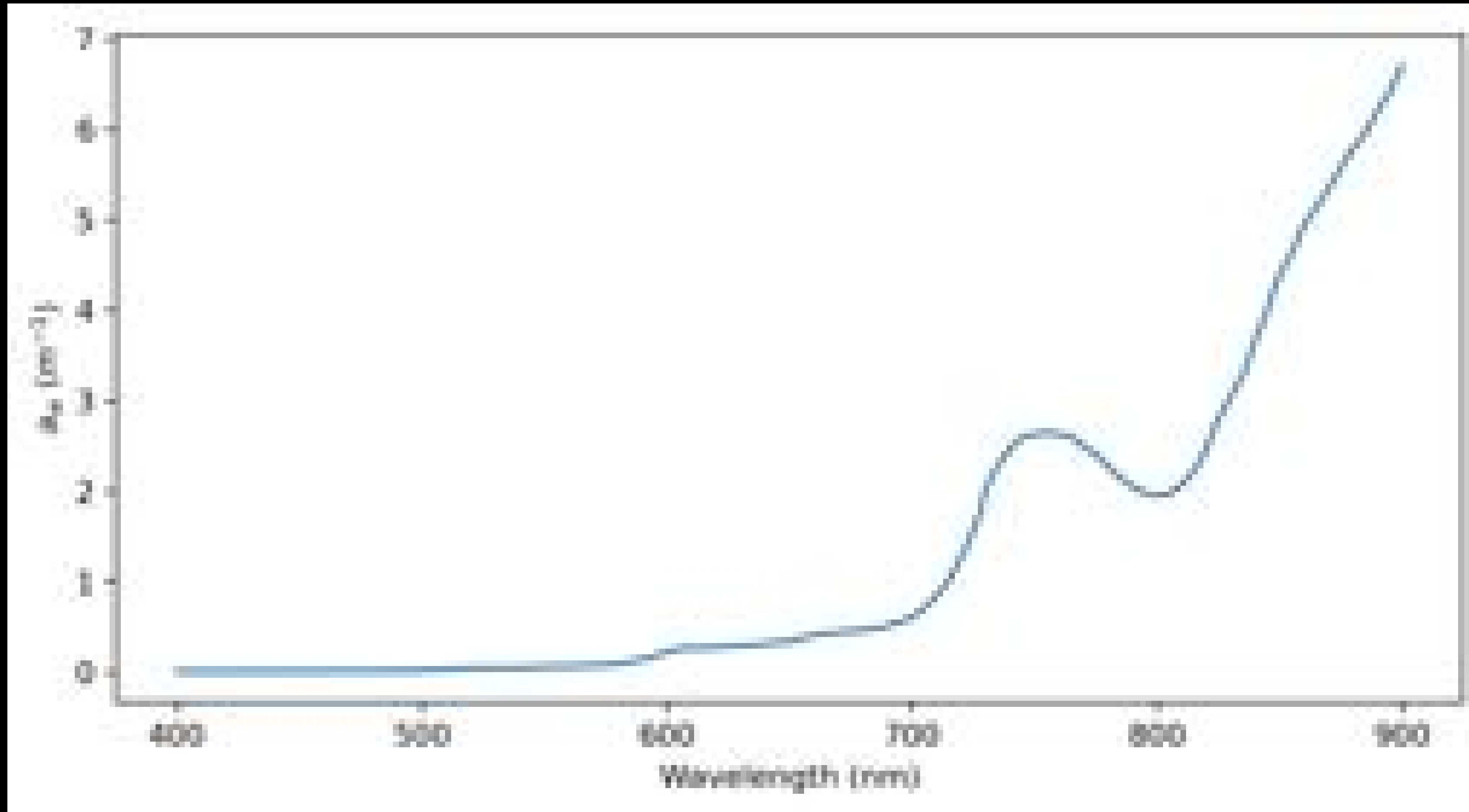
Aerosol estimation

2) Modified ocean colour approach, e.g.

- Hu et al. (2000), Ruddick et al. (2000) ~ spatial context/stability of aerosol
- DSF - Vanhellemont and Ruddick (2018) ~ spatial context, use of VIS-SWIR, potentially land
- RAdCor - Castagna and Vanhellemont (2025) ~ generalisation to heterogeneous surface
- SeaDAS/l2gen, Bailey et al. (2010) ~ non-zero NIR from chl
- BPAC, MERIS/OLCI (Moore et al. 1999, 2017)
- SeaDAS/l2gen, NOAA/msl12, Wang and Shi (2007) ~ zero SWIR



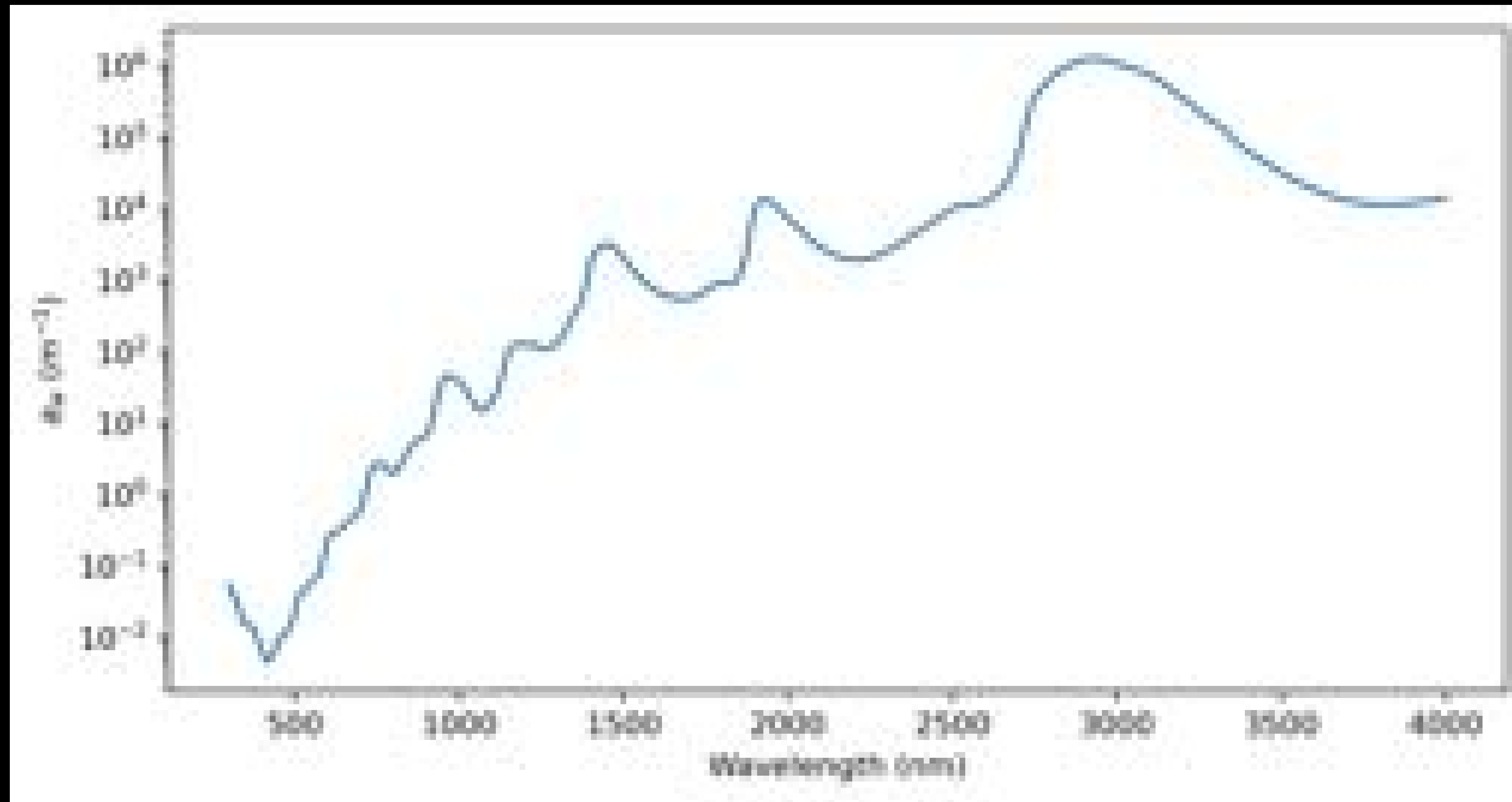
Water absorption



WOPP, Röttgers et al. (2011), T 20°C, S 34 PSU

Water absorption

aw orders of magnitude greater
at ~1600 and ~2200 nm



WOPP, Röttgers et al. (2011), T 20°C, S 34 PSU

Aerosol estimation

3) Approaches which include or rely on water models, e.g.

- POLYMER, Steinmetz et al. (2011)
- C2RCC, Roland Doerffer and Helmut Schiller 1990s-2000s, Müller et al. (2025)
- OC-SMART, Fan et al. (2021)

POLYMER

Part 1

Part 2

Part 3

Steinmetz et al. (2011)

The radius R_{eff} measured at wavelength λ at the top of the atmosphere (TOA) with a solar zenith angle θ_0 is converted to differential R_{eff} by interpolation to commercial solar radiation R_0 .

Year	Number of cases	Percentage of cases
1990	10	10.0
1991	15	15.0
1992	20	20.0
1993	25	25.0
1994	30	30.0
1995	35	35.0
1996	40	40.0
1997	45	45.0
1998	50	50.0
1999	55	55.0
2000	60	60.0
2001	65	65.0
2002	70	70.0
2003	75	75.0
2004	80	80.0
2005	85	85.0
2006	90	90.0
2007	95	95.0
2008	100	100.0
2009	105	105.0
2010	110	110.0
2011	115	115.0
2012	120	120.0
2013	125	125.0
2014	130	130.0
2015	135	135.0
2016	140	140.0
2017	145	145.0
2018	150	150.0
2019	155	155.0
2020	160	160.0
2021	165	165.0
2022	170	170.0
2023	175	175.0
2024	180	180.0
2025	185	185.0
2026	190	190.0
2027	195	195.0
2028	200	200.0
2029	205	205.0
2030	210	210.0
2031	215	215.0
2032	220	220.0
2033	225	225.0
2034	230	230.0
2035	235	235.0
2036	240	240.0
2037	245	245.0
2038	250	250.0
2039	255	255.0
2040	260	260.0
2041	265	265.0
2042	270	270.0
2043	275	275.0
2044	280	280.0
2045	285	285.0
2046	290	290.0
2047	295	295.0
2048	300	300.0
2049	305	305.0
2050	310	310.0
2051	315	315.0
2052	320	320.0
2053	325	325.0
2054	330	330.0
2055	335	335.0
2056	340	340.0
2057	345	345.0
2058	350	350.0
2059	355	355.0
2060	360	360.0
2061	365	365.0
2062	370	370.0
2063	375	375.0
2064	380	380.0
2065	385	385.0
2066	390	390.0
2067	395	395.0
2068	400	400.0
2069	405	405.0
2070	410	410.0
2071	415	415.0
2072	420	420.0
2073	425	425.0
2074	430	430.0
2075	435	435.0
2076	440	440.0
2077	445	445.0
2078	450	450.0
2079	455	455.0
2080	460	460.0
2081	465	465.0
2082	470	470.0
2083	475	475.0
2084	480	480.0
2085	485	485.0
2086	490	490.0
2087	495	495.0
2088	500	500.0
2089	505	505.0
2090	510	510.0
2091	515	515.0
2092	520	520.0
2093	525	525.0
2094	530	530.0
2095	535	535.0
2096	540	540.0
2097	545	545.0
2098	550	550.0
2099	555	555.0
2100		

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$$\|u_{\alpha,\beta}(t)\|_{L^2(\mathbb{R}^n)} \leq \|u_0\|_{L^2(\mathbb{R}^n)} + \int_0^t \|u_{\alpha,\beta}(s)\|_{L^2(\mathbb{R}^n)} ds + \int_0^t \|f(s)\|_{L^2(\mathbb{R}^n)} ds. \quad (2.10)$$

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where d_{ij} represents the number of weights the network contains on the coupling from

2002-2003-2004-2005

1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 2679, 26

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(C) $\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n f\left(\frac{k}{n}\right) = \int_0^1 f(x) dx$ (B) is True and (D) is False.

(D) $\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n f\left(\frac{k}{n}\right) = \int_0^1 f(x) dx$ (B) is False and (D) is True.

The observed frequency of the *strongylid* subgenus was 10 percent high. The scheme is the following:

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2. For the current values of $\log T_{\text{eff}}$ and $\log g_{\text{eff}}$, and for each parallax ϖ among the 15 selected bands, calculate the rapid oscillation spectrum $\sigma_{\text{osc}}^2(\log T_{\text{eff}}, \log g_{\text{eff}}, \varpi)$. Note the model spectrum is defined as:

2. Calculating the values of α_{11} , α_{12} and α_{22} obtained by the polynomial fit for all cases (equation 1).

Received 12 July 2006; accepted 12 September 2006; first published online 12 October 2006

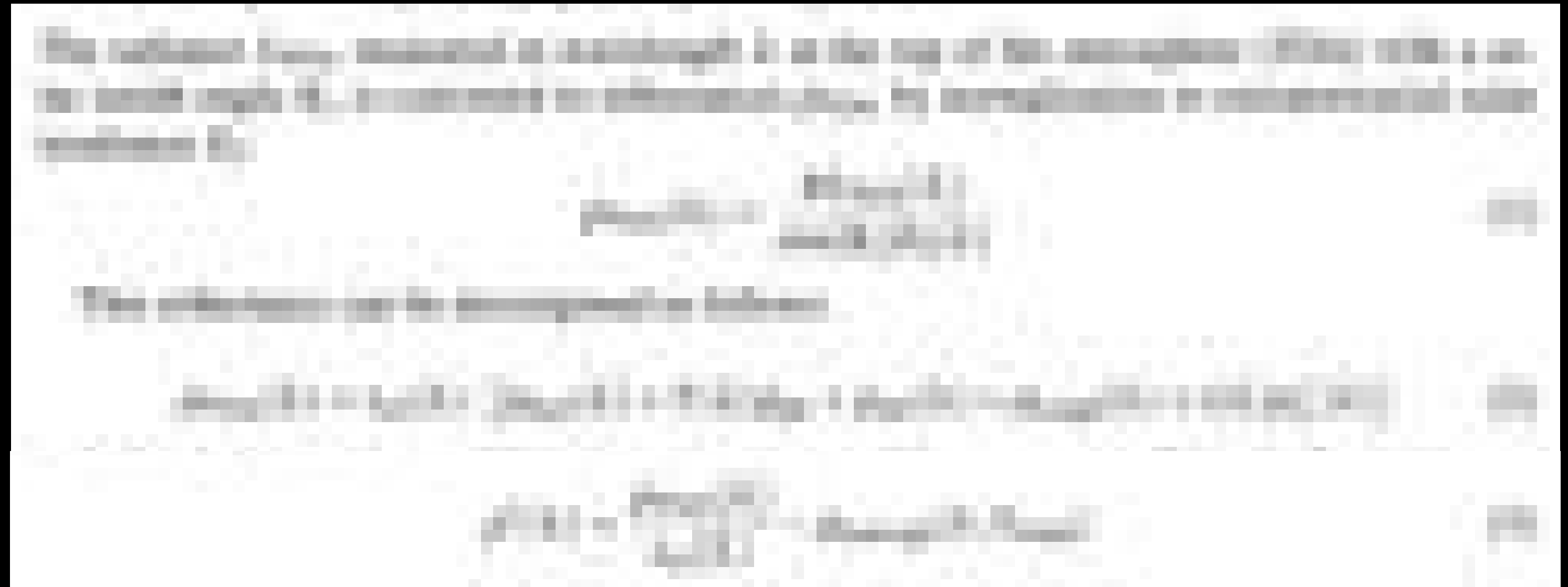
1. *Journal of Management Studies*, 1996, 33, 1, 1-14.

$$d(\mathbf{y}) = \left[\sum_{i=1}^n \left(\frac{1}{2} \log \frac{1}{2\pi} - \frac{1}{2} \log \frac{1}{2\pi} - \frac{1}{2} \log \frac{1}{2\pi} - \frac{1}{2} \log \frac{1}{2\pi} \right) \right]$$

Source: *U.S. Census Bureau, 1997*

POLYMER

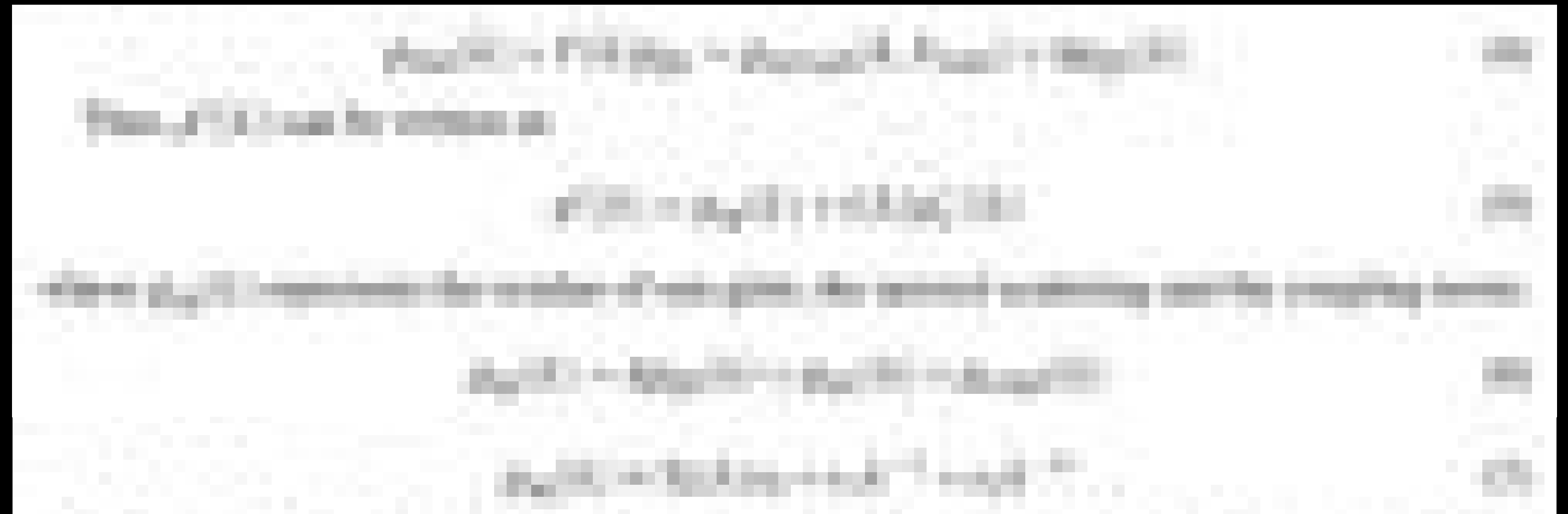
Step 1 ~ ρ_{TOA}
 $\rho' : \rho_{\text{TOA}} - \rho_{\text{Rayleigh}}$



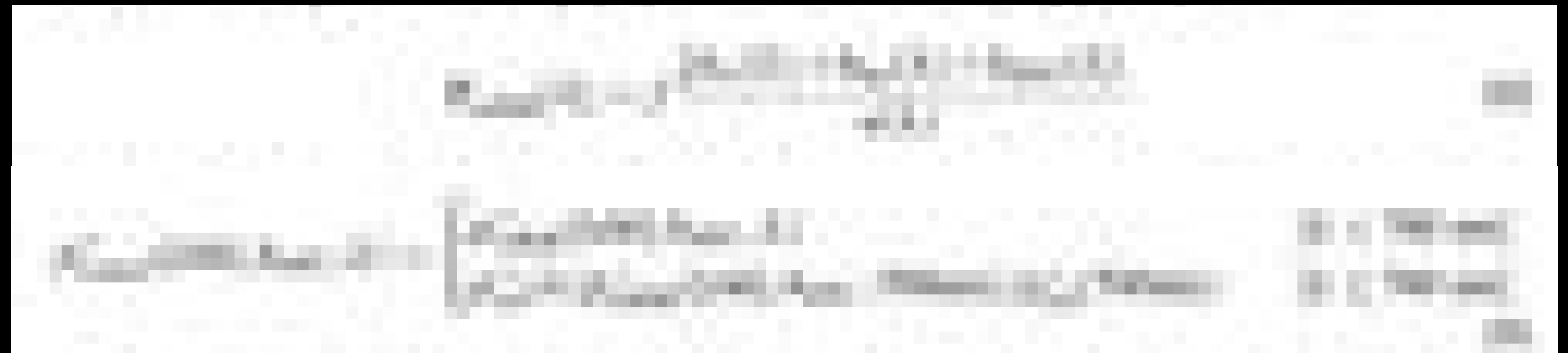
Steinmetz et al. (2011)

POLYMER

Step 2 ~ model
 $\rho_{ag} + \rho_w$



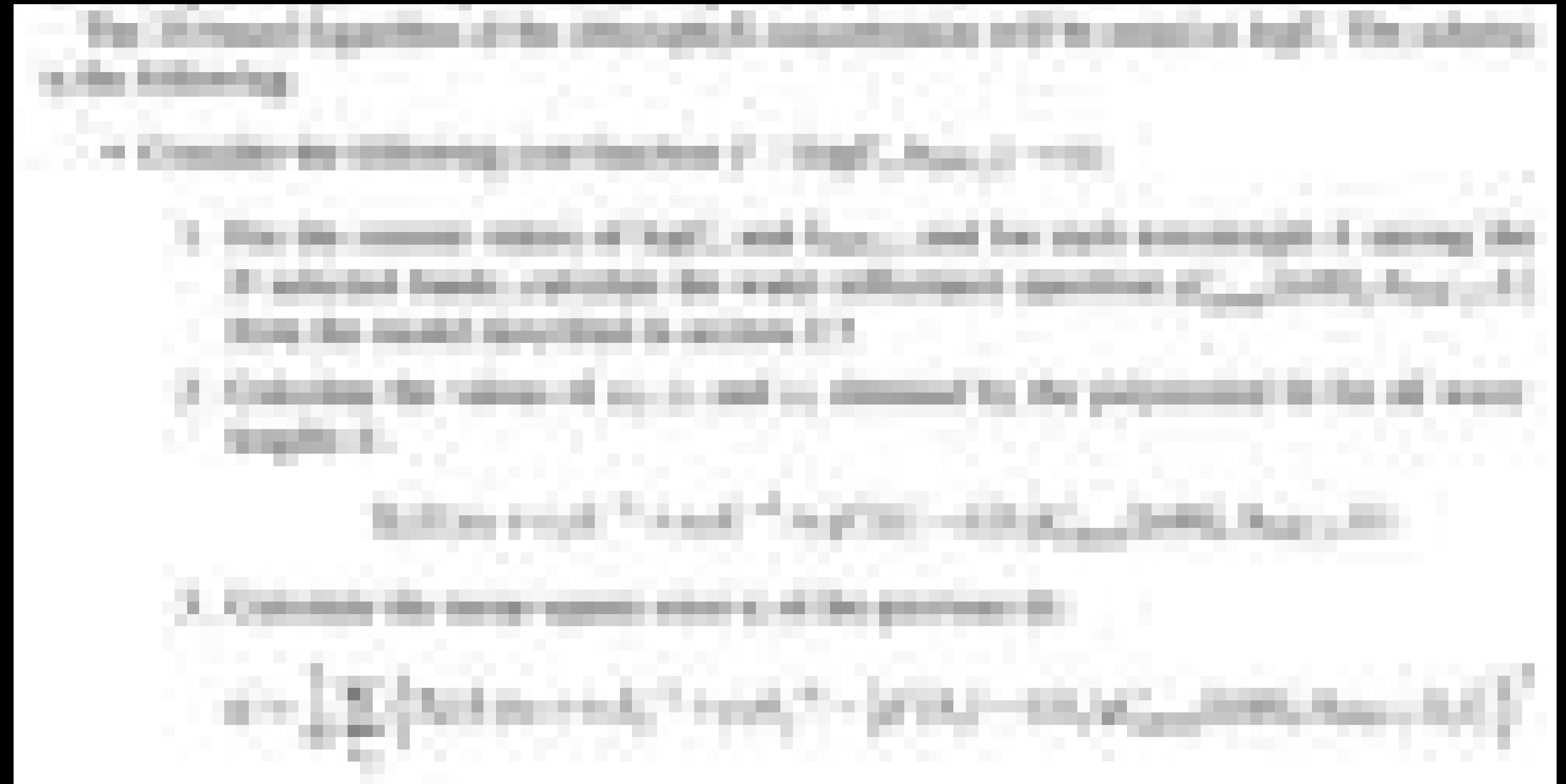
ρ_{ag} : coupled residual aerosol
and glint reflectance



ρ_w : function of Chl and b_b

Steinmetz et al. (2011)

Step 3 ~ optimise
 $\rho_{ag} + \rho_w$



iterate over Chl , b_b , c_0 , c_1 , c_2



ρ_w computed using final c_0 , c_1 , c_2

Steinmetz et al. (2011)

C2RCC

Müller et al. (2025)



C2RCC

Part 1

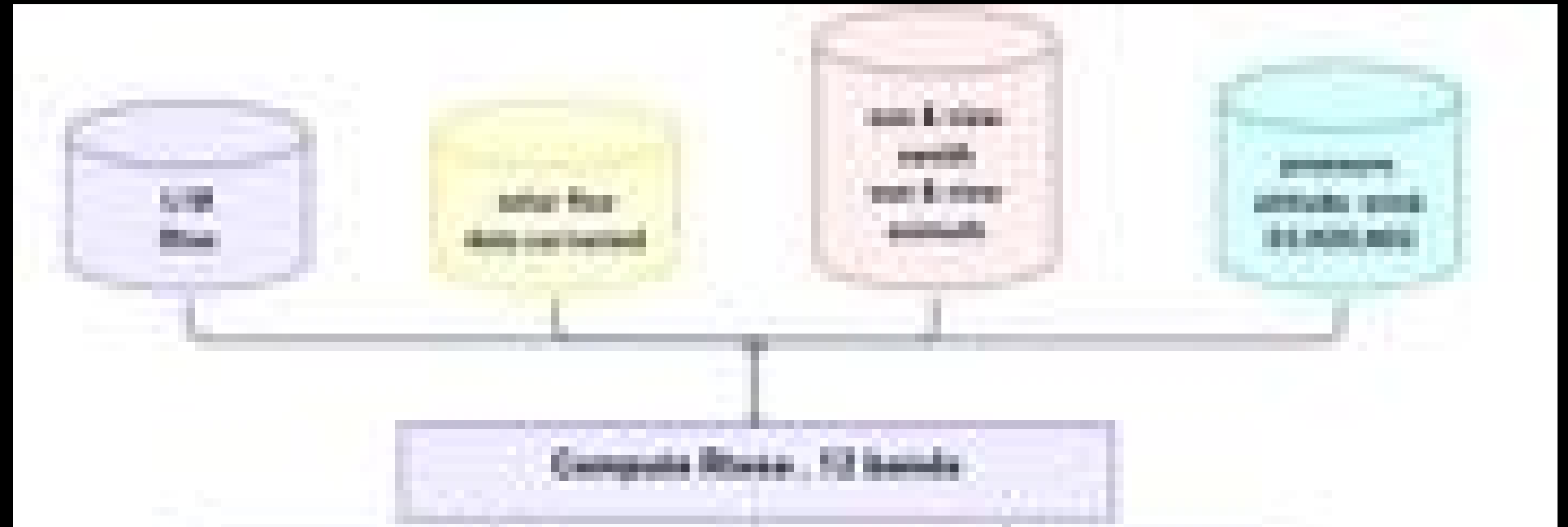
Part 2

Part 3



C2RCC

Part 1 ~ standard
ocean colour

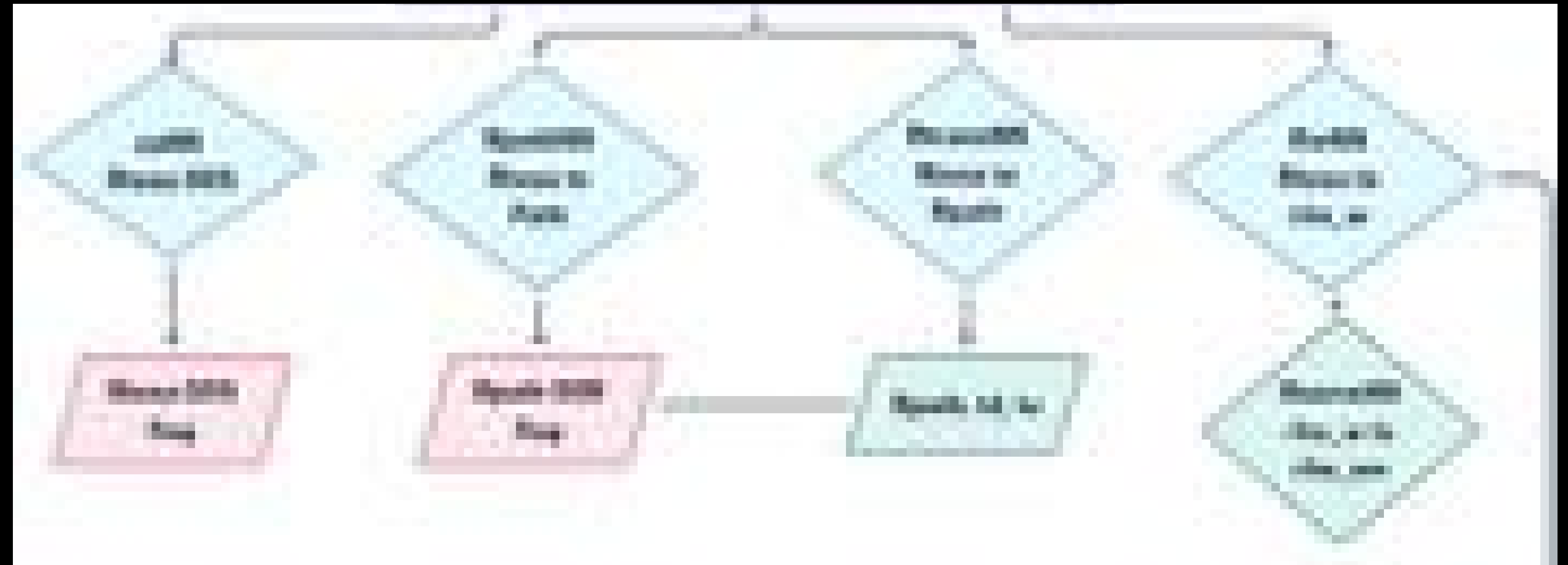


**Rtosa = Reflectance at
Top-Of-Standard-Atmosphere**

Müller et al. (2025)

C2RCC

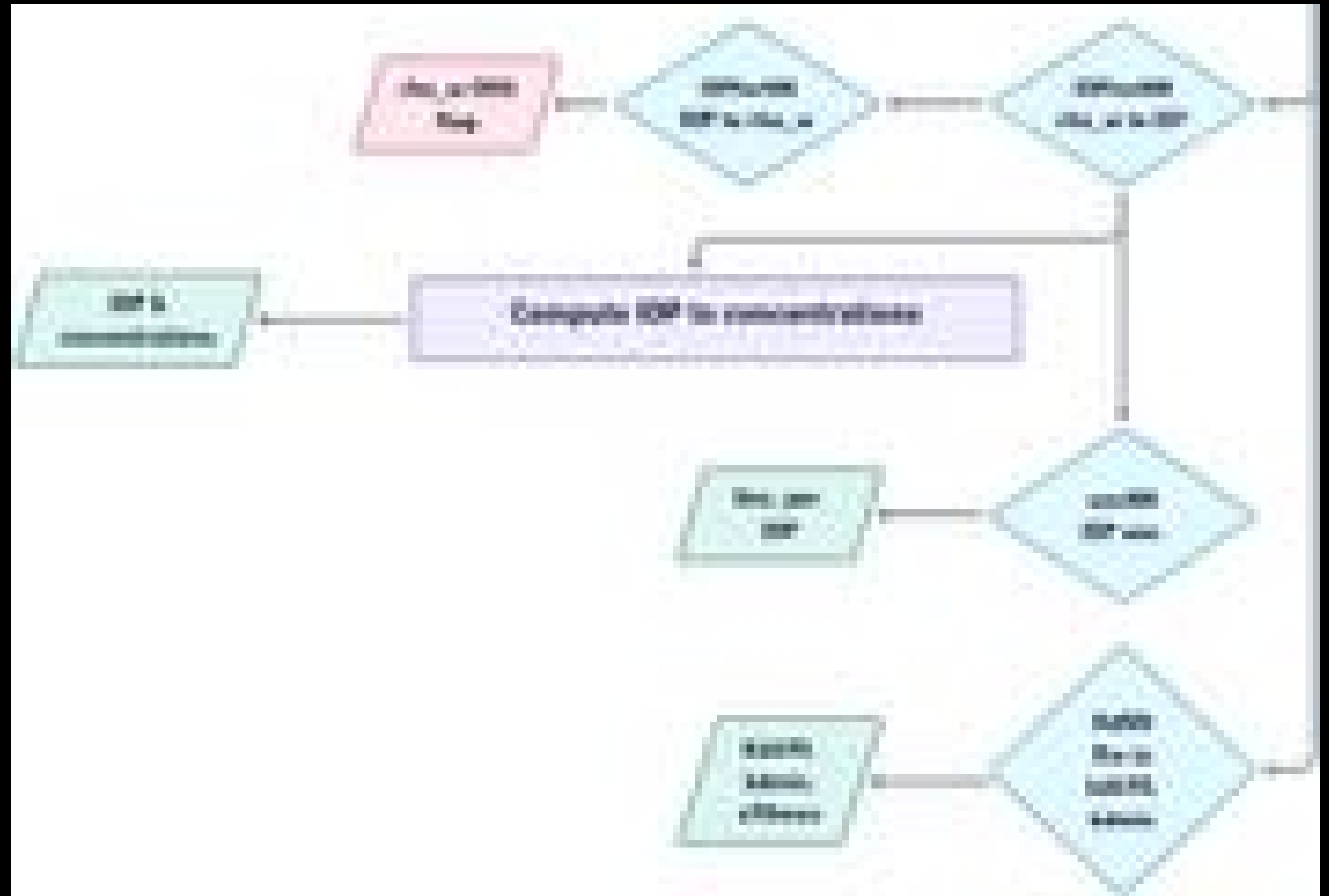
Part 2 ~
Rtosa $\rightarrow$ NN pw(n)



Müller et al. (2025)

C2RCC

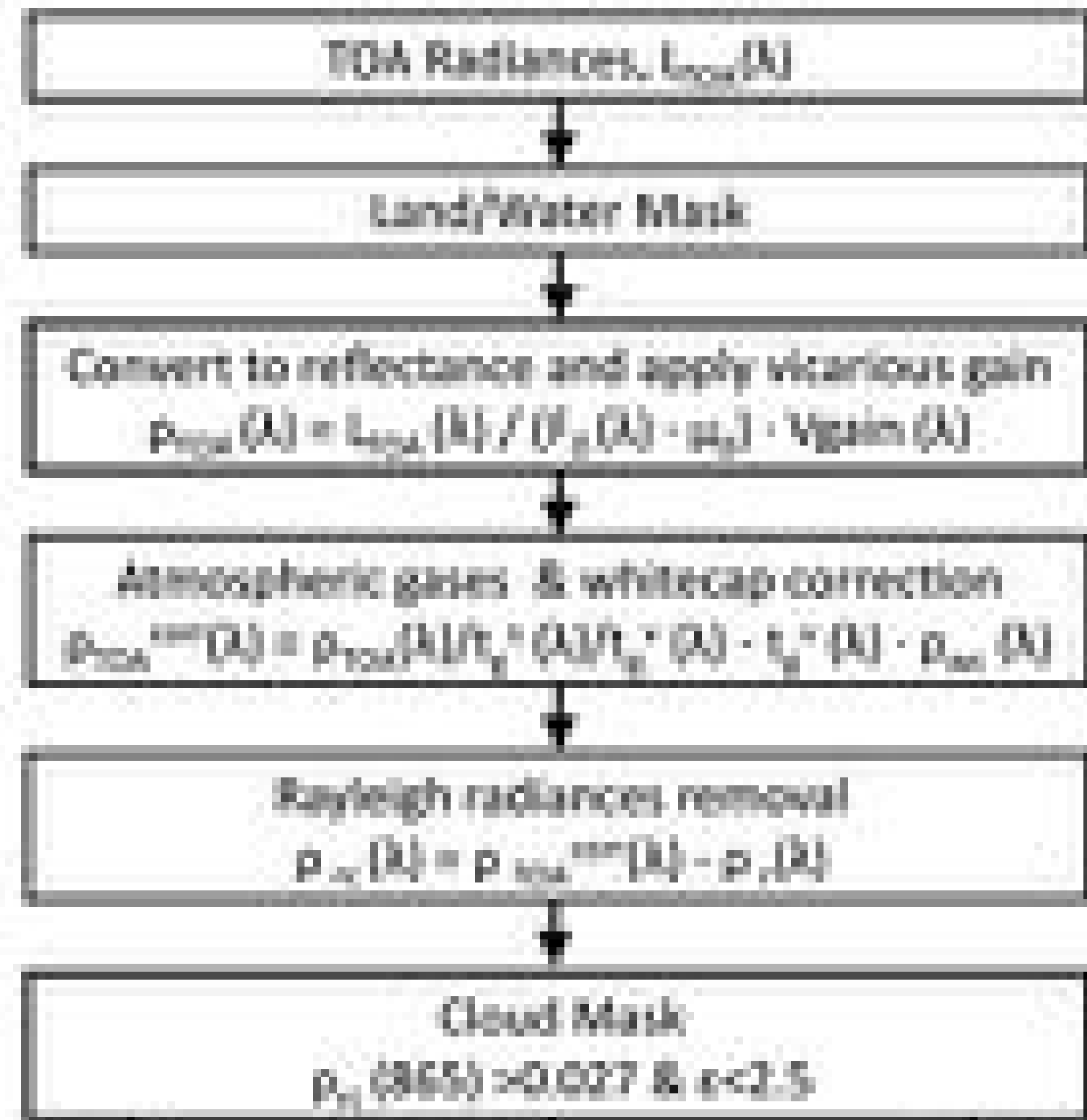
Part 3 ~
 $\rho_w \rightarrow$ NN IOP



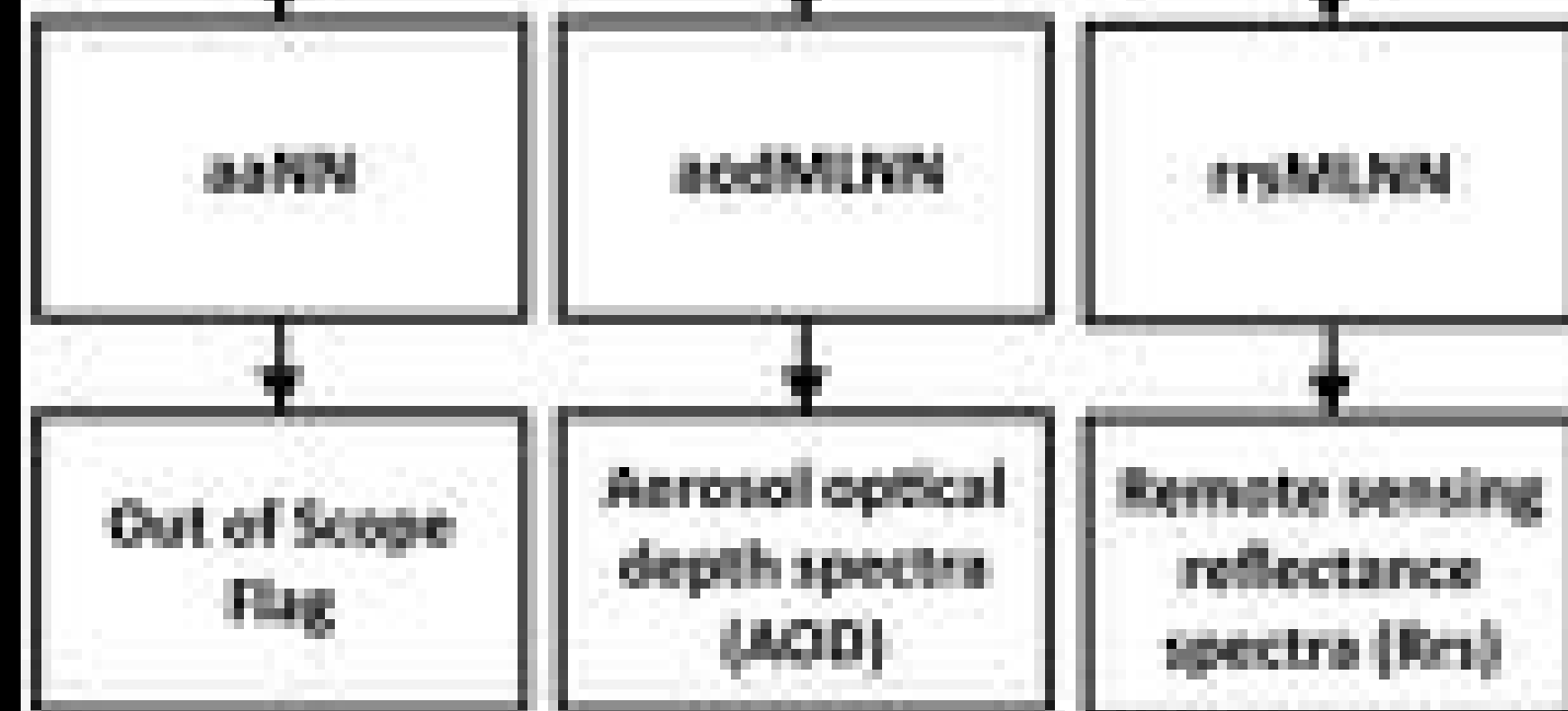
Müller et al. (2025)

OC-SMART

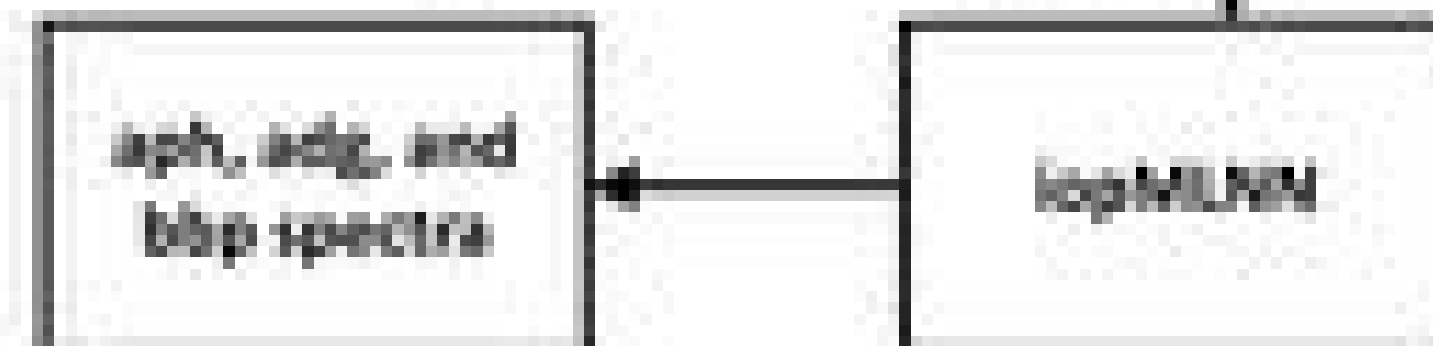
Part 1



Part 2



Part 3

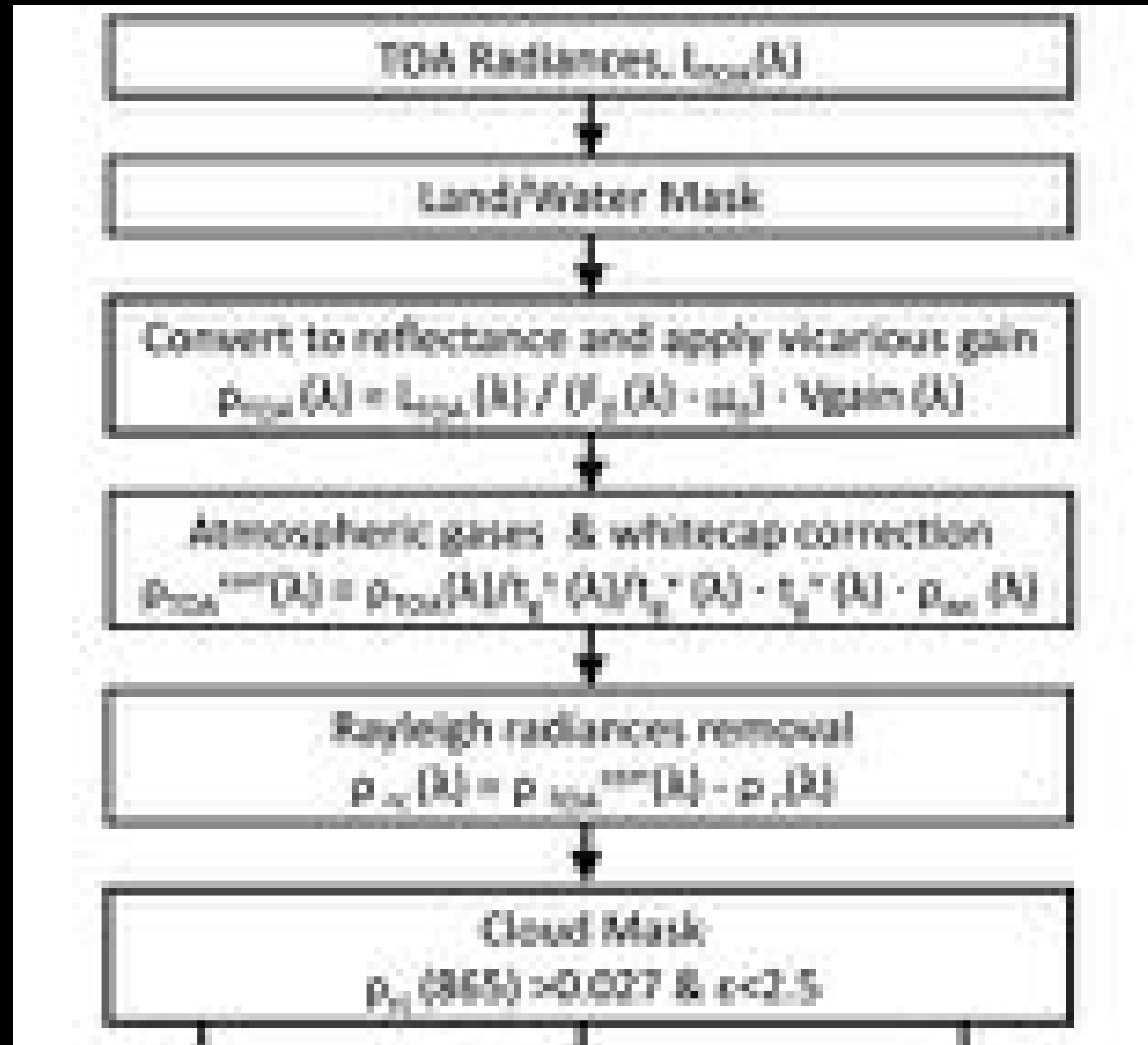


Fan et al. (2021)

OC-SMART

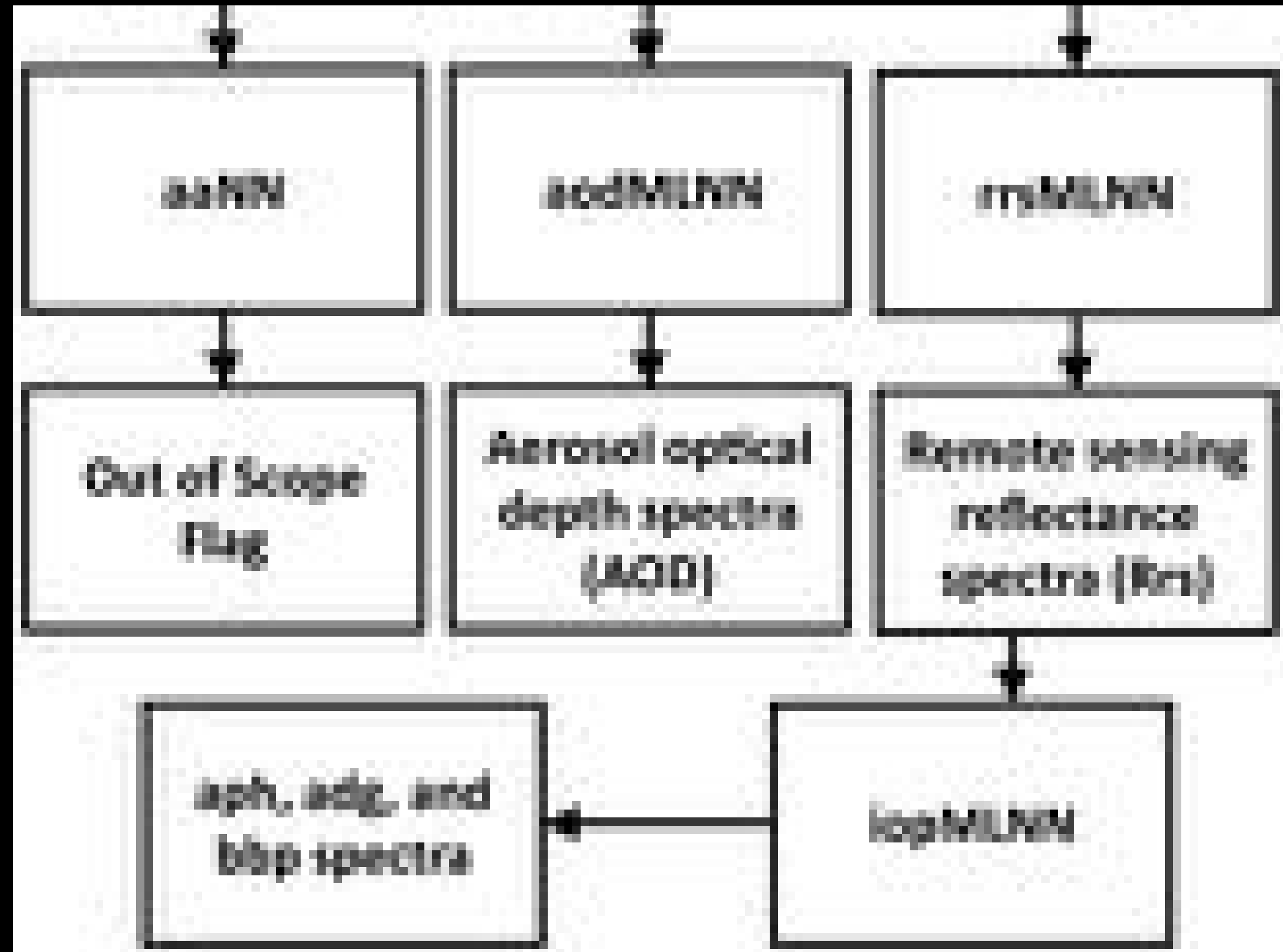
Part 1 ~ standard
ocean colour

Fan et al. (2021)



OC-SMART

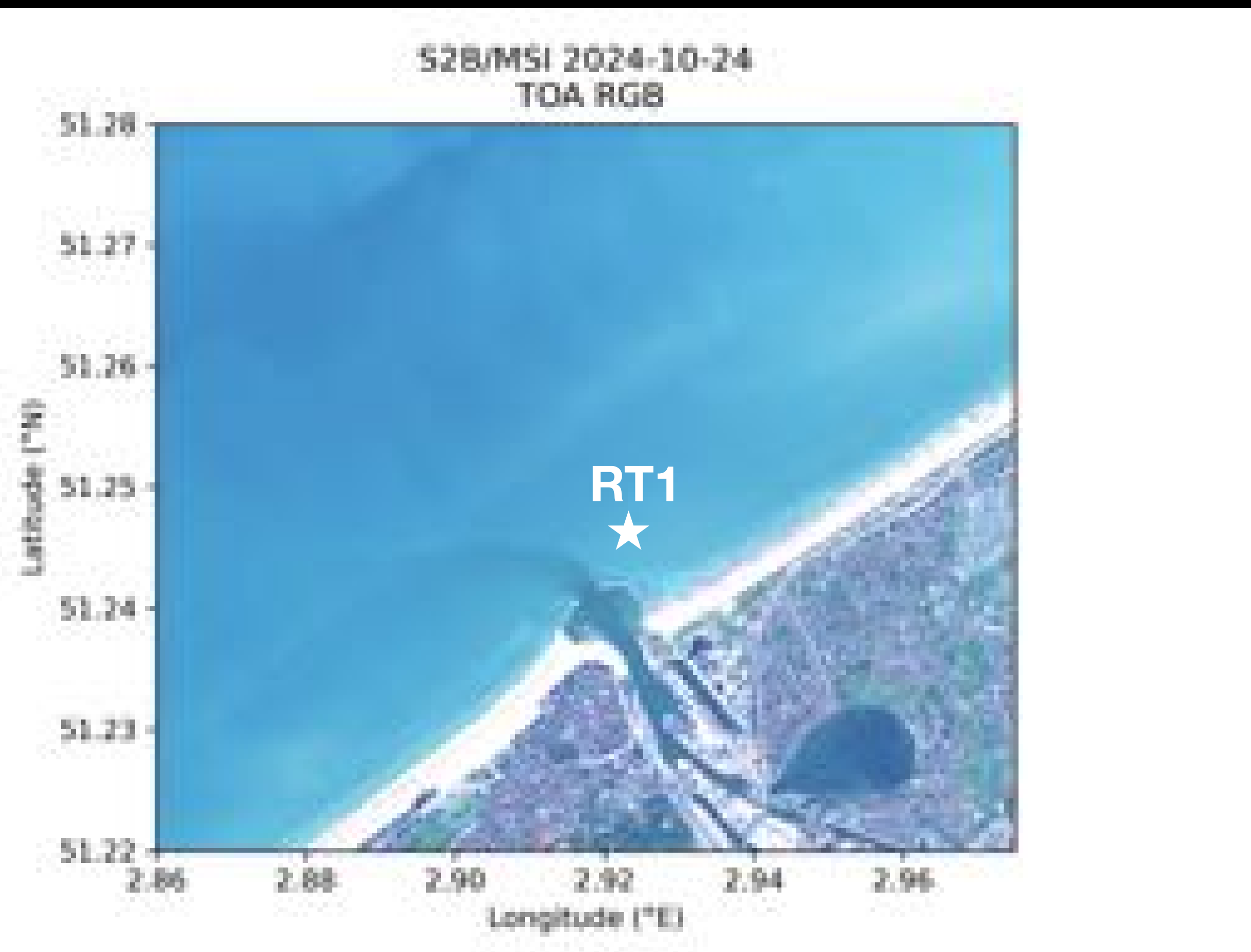
Part 2 ~ prc ->
NN Rrs



Fan et al. (2021)

Part 3 ~ Rrs ->
NN IOP

Example - Belgian Coastal Zone



TOA



Research Tower 1
~900 m from shore

PANTHYR
autonomous
hyperspectral
radiometer

PI: Dieter Vansteenwegen (VLIZ)

PANTHYR

- Two TriOS RAMSES (L, E)
- Mounted on pan and tilt head
- Measurements every 20 minutes
- RAA 90/135/225/270° VNA 40°
- 3x Ed, 3x Ld, 11x Lu, 3x Ld, 3x Ed
- Valid 5/6 Ed and Ld 9/11 Lu
- Effective Fresnel using Mobley 1999
- QC using Ruddick et al. 2005/2006, custom

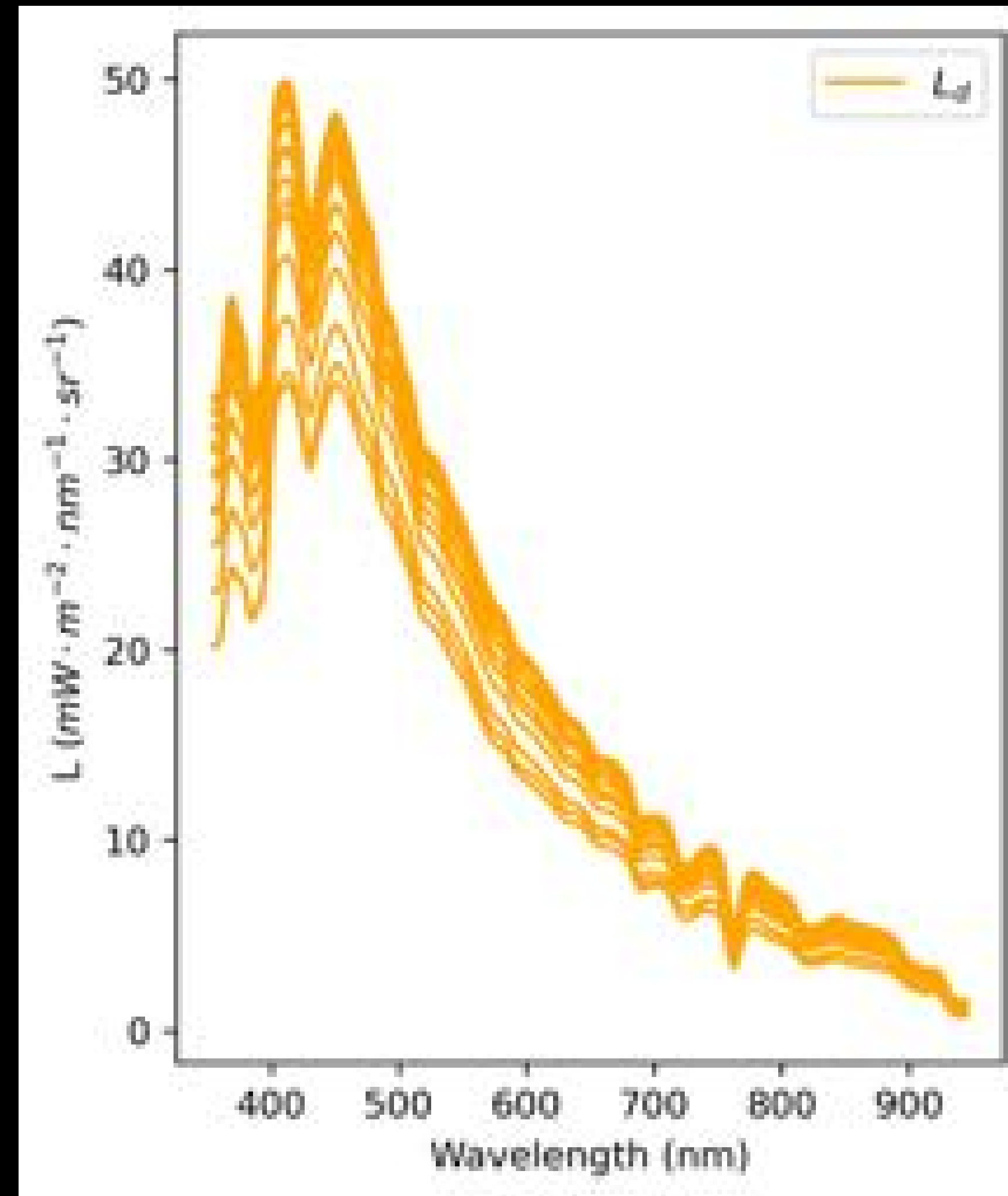
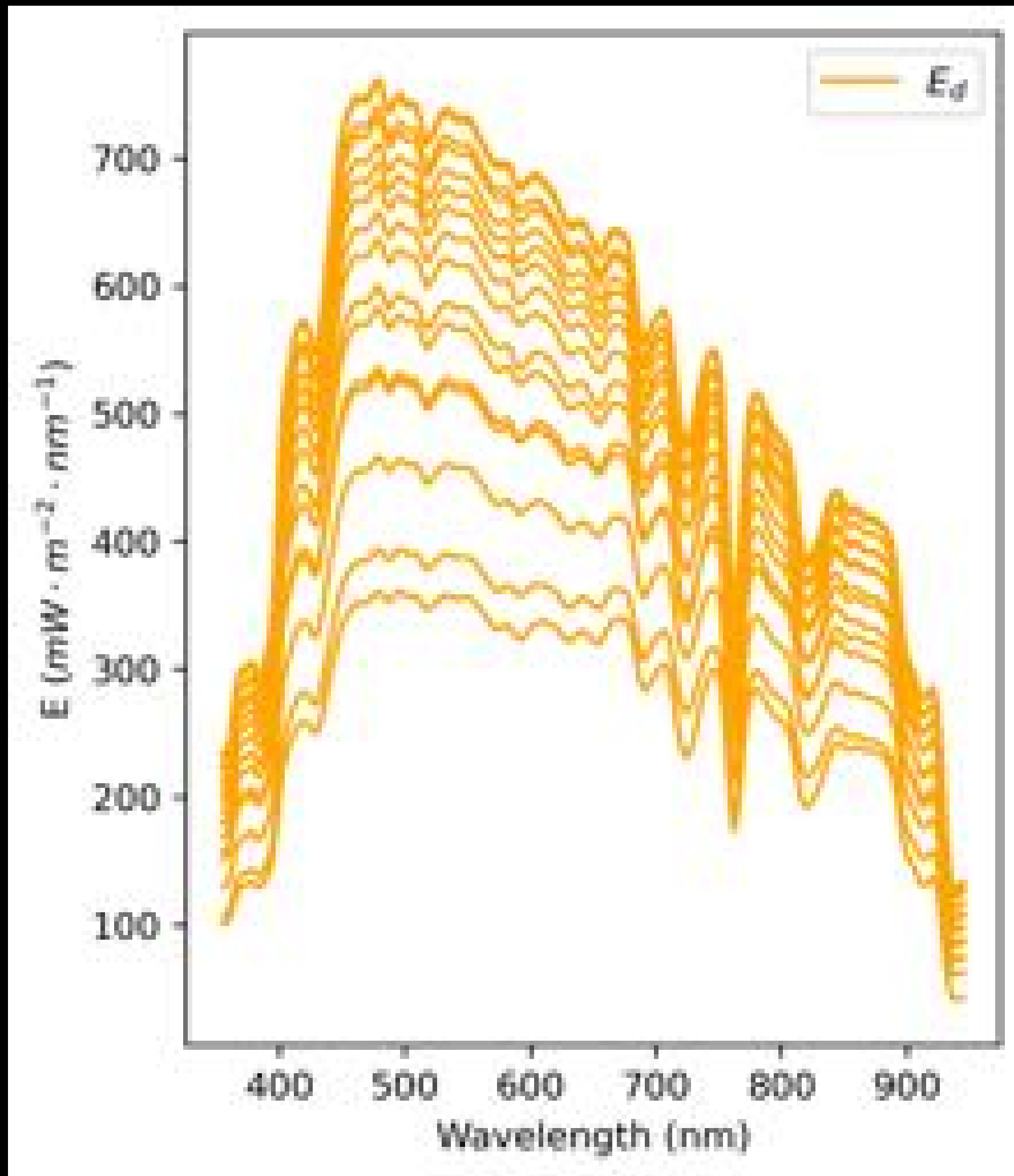
Vansteenwegen et al. (2019)



<https://waterhypernet.org/equipment/>

2024-10-24

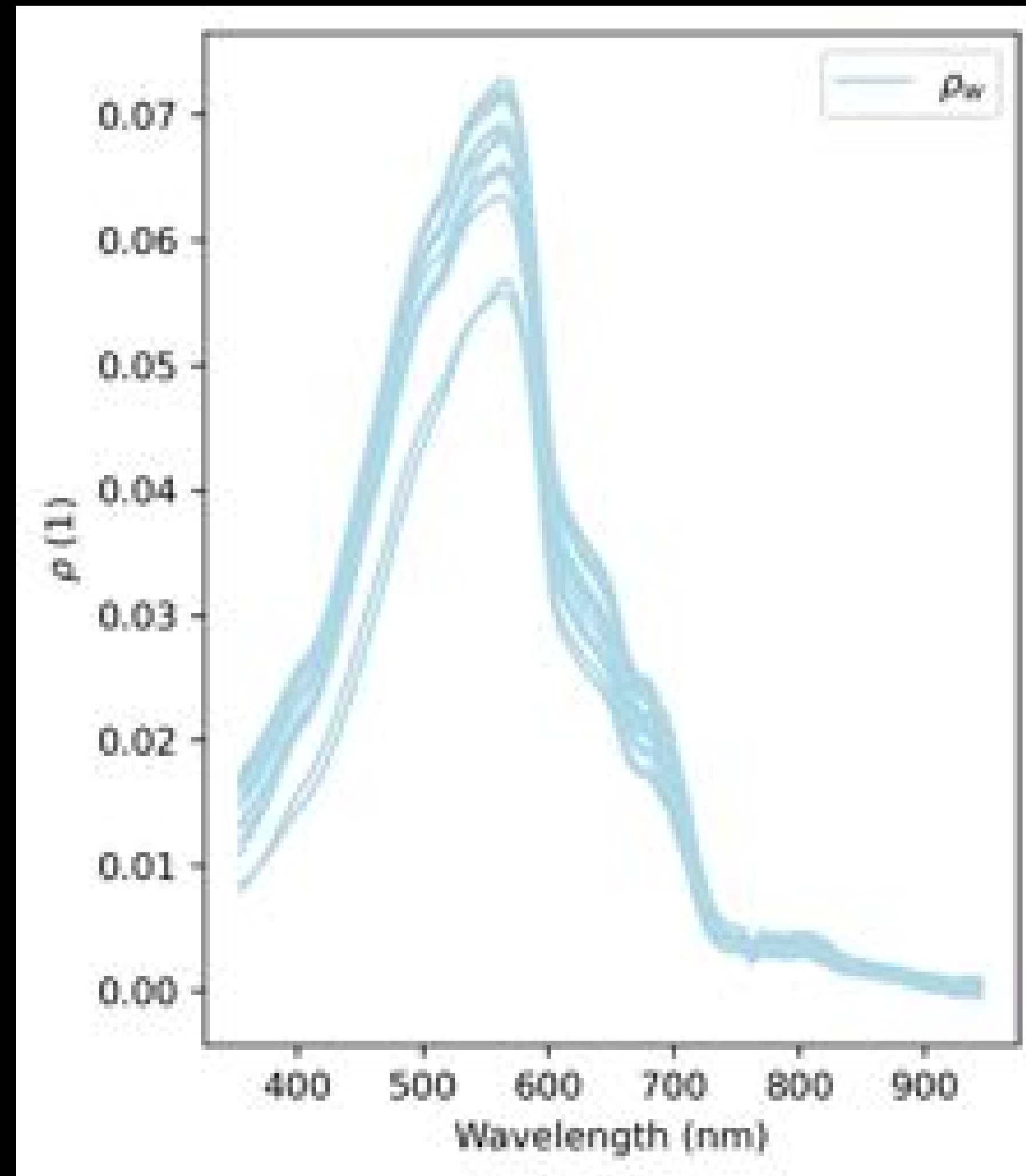
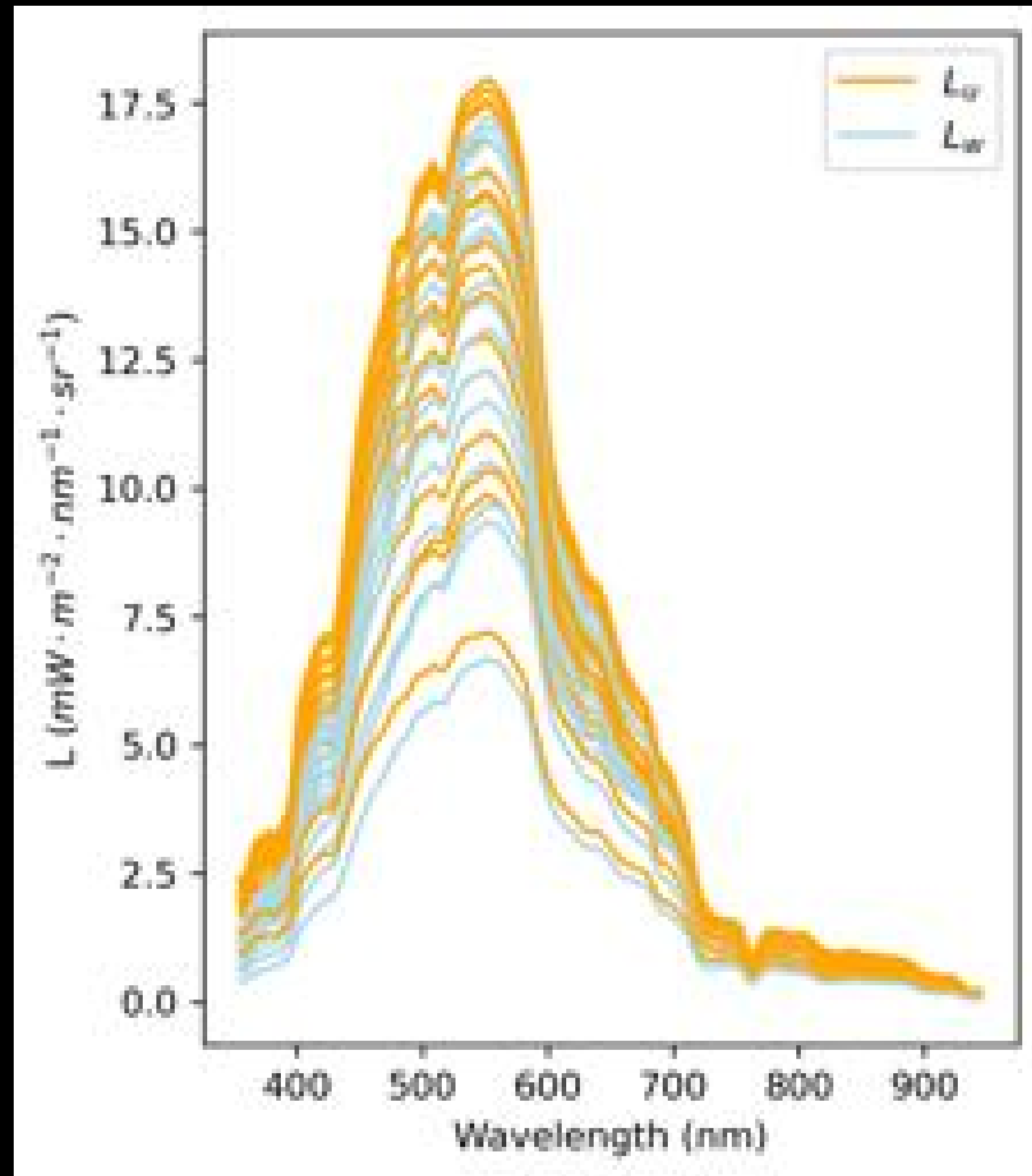
PANTHYR



17 measurements at 270° relative azimuth passing QC (8:30 - 14:40UTC)

2024-10-24

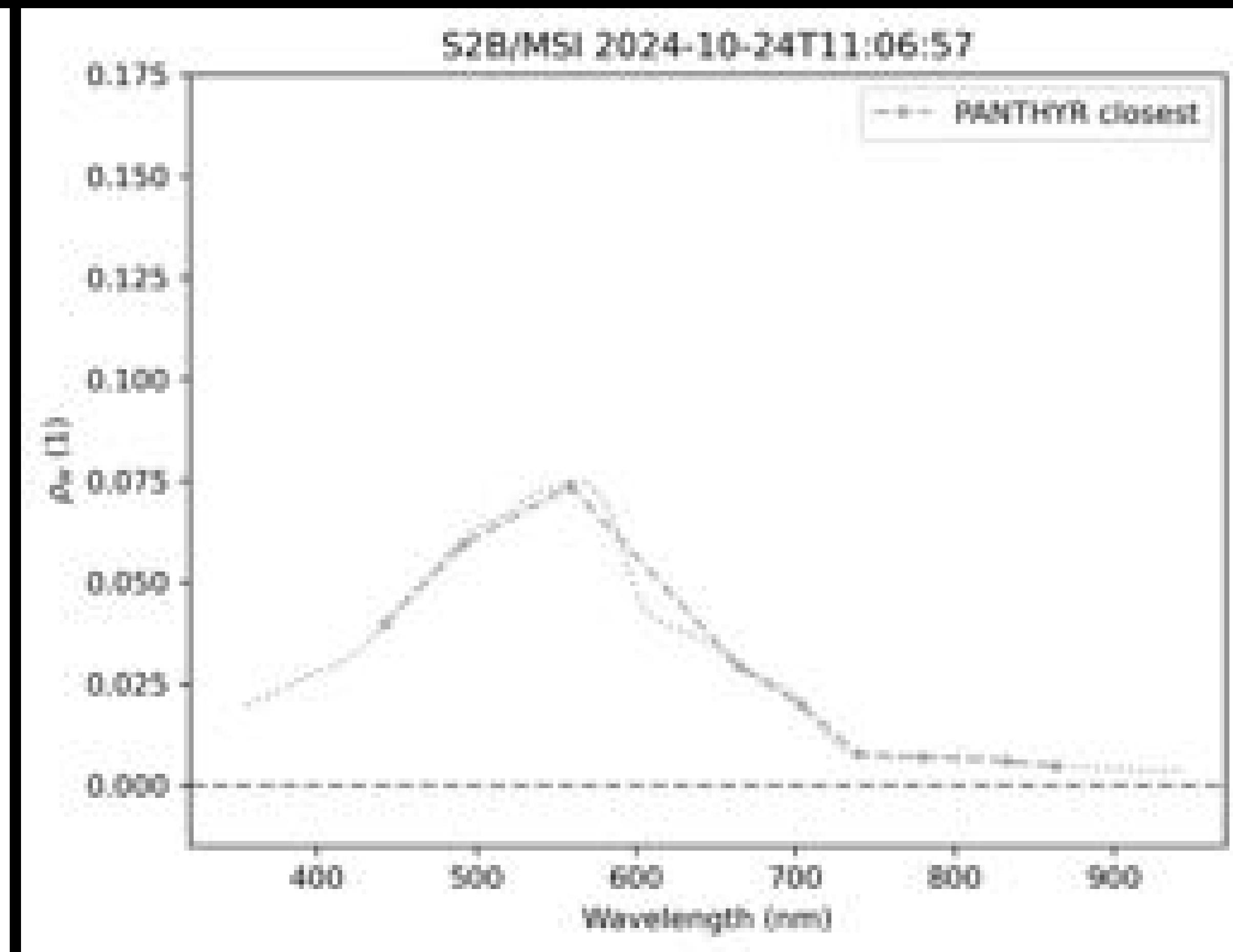
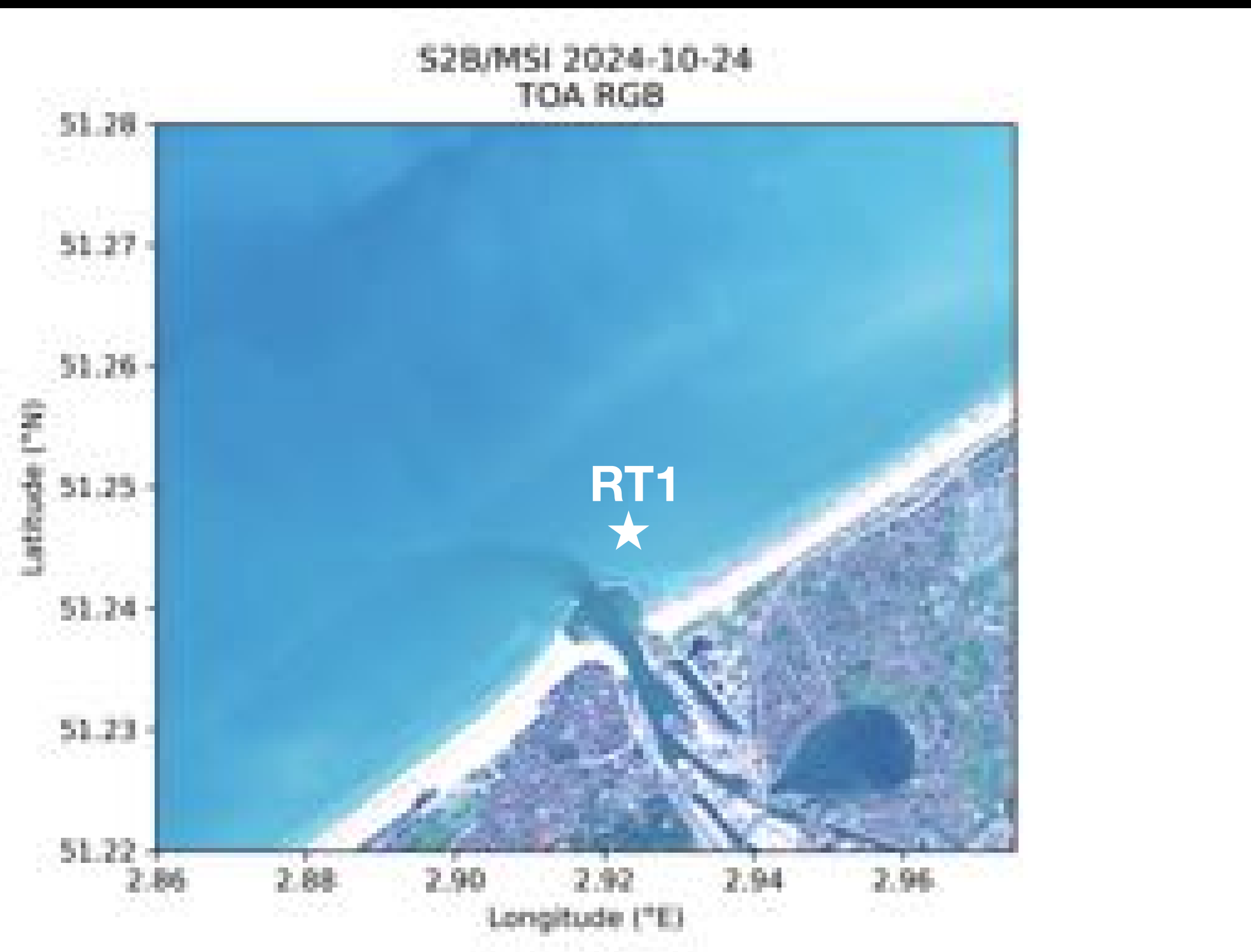
PANTHYR



17 measurements at 270° relative azimuth passing QC (8:30 - 14:40UTC)

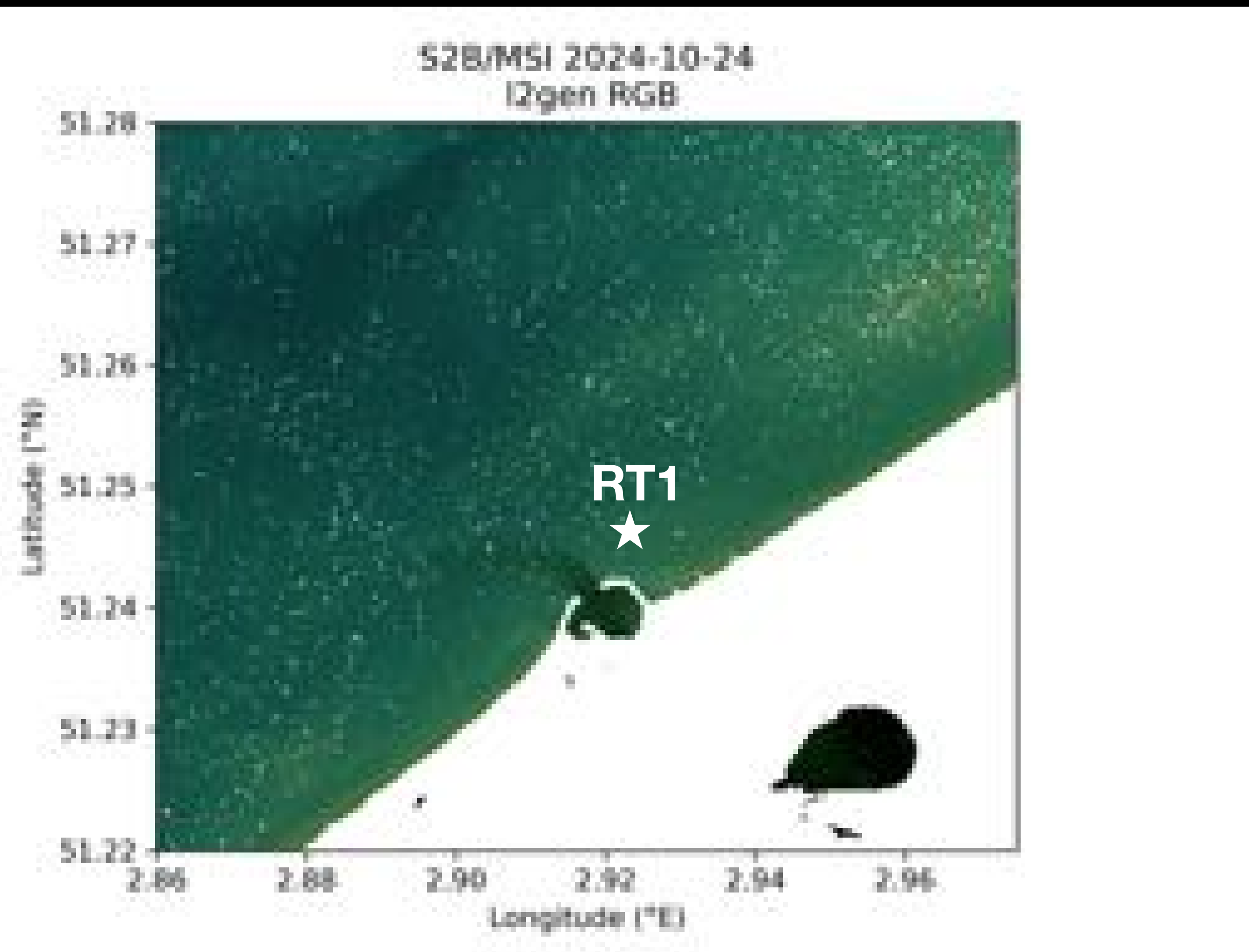
TOA 2024-10-24

PANTHYR

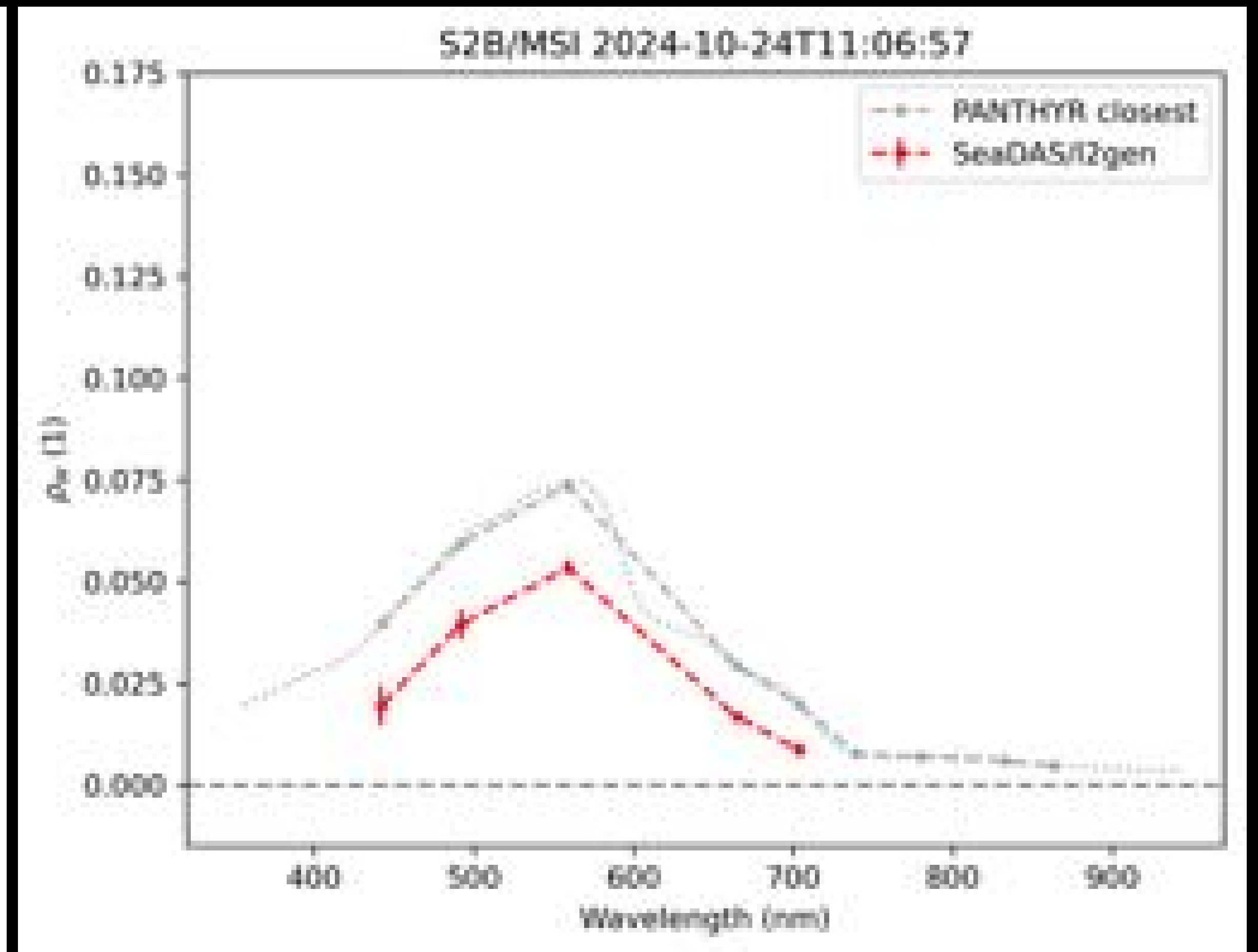


Moderately turbid, no high Chla (665 nm dip absent)

I2gen

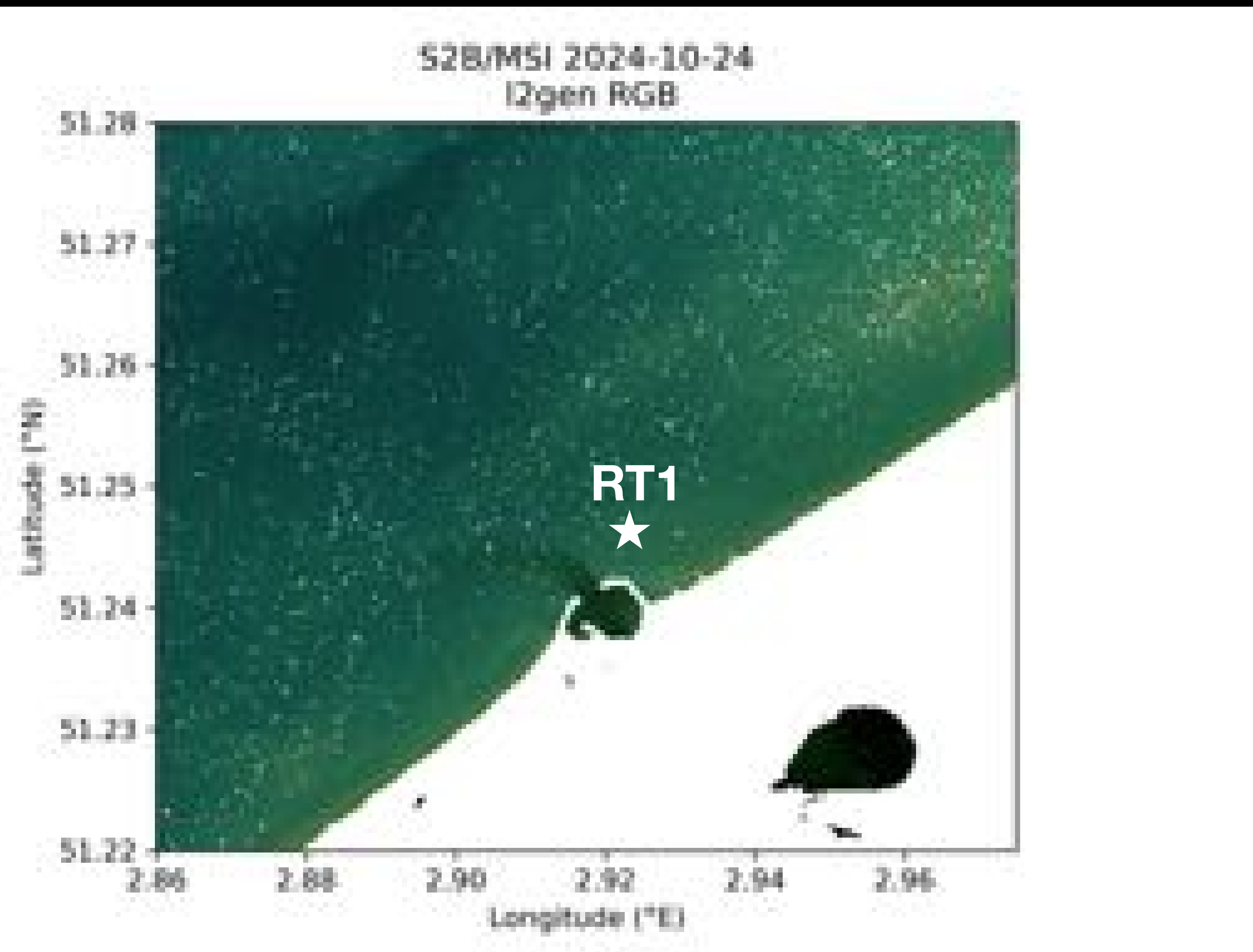


green-blueish appearance, some scattered pixels
masked (ATMFAIL)

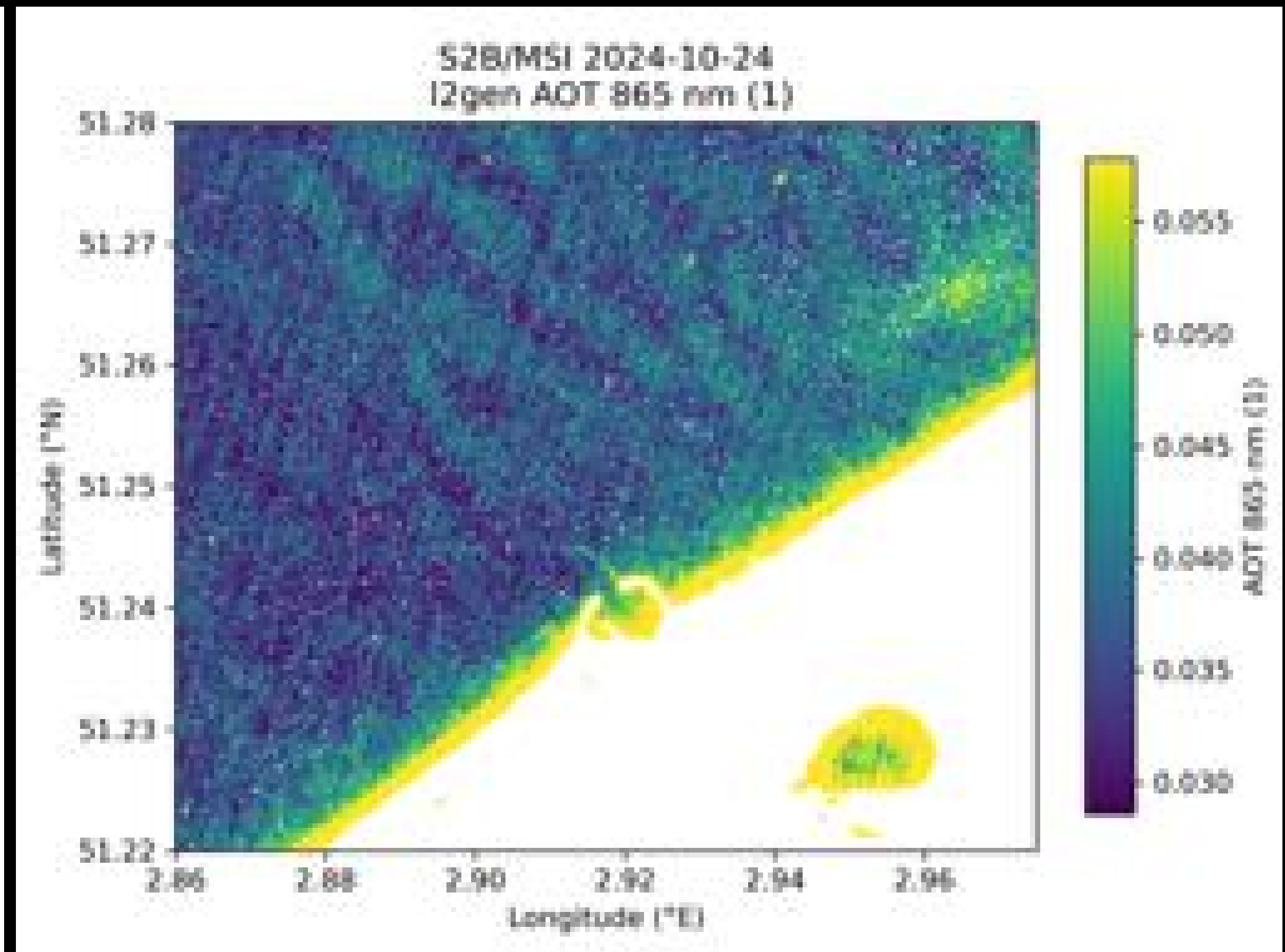


fairly flat overcorrection

I2gen

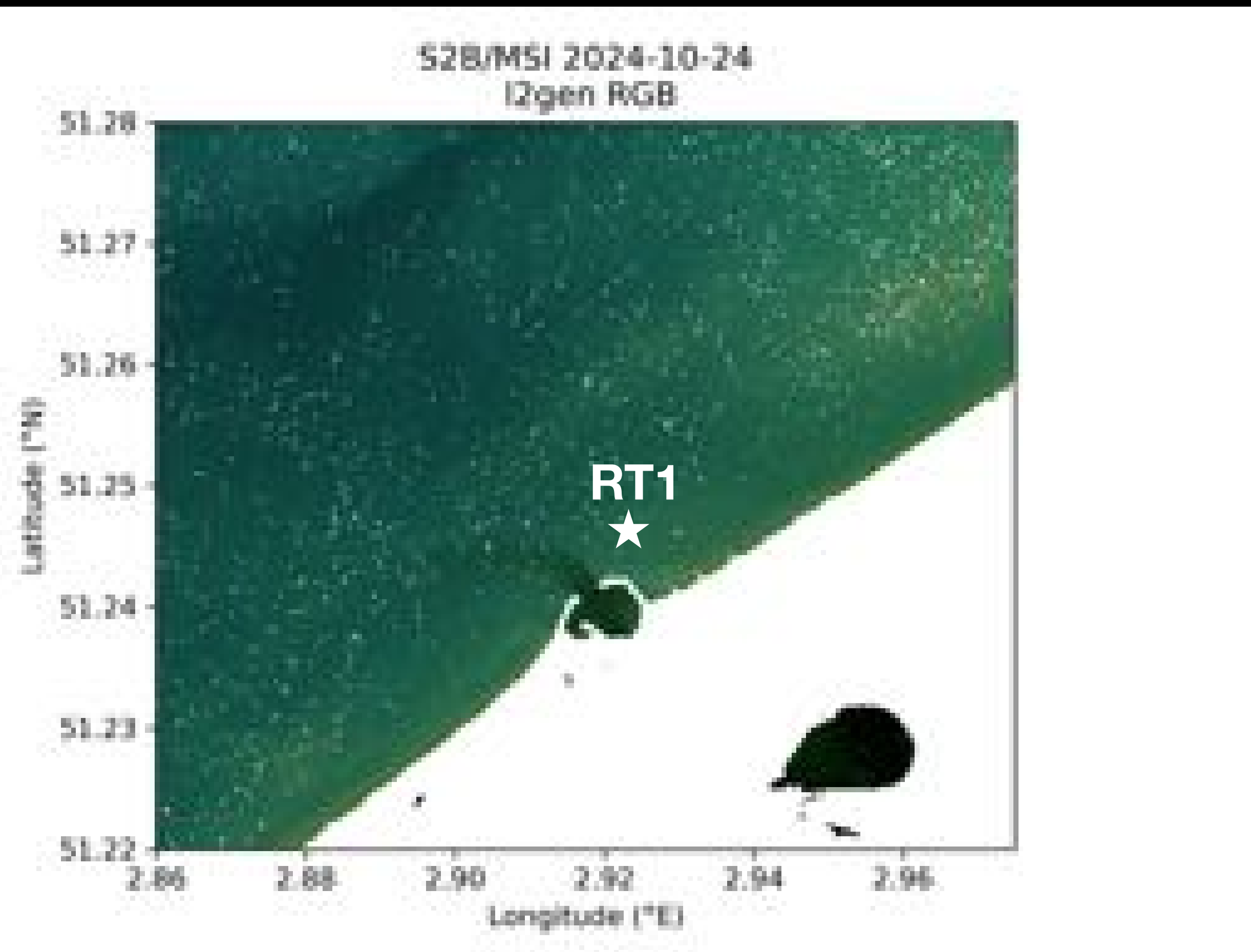


noisy aerosol products -> noisy Rrs

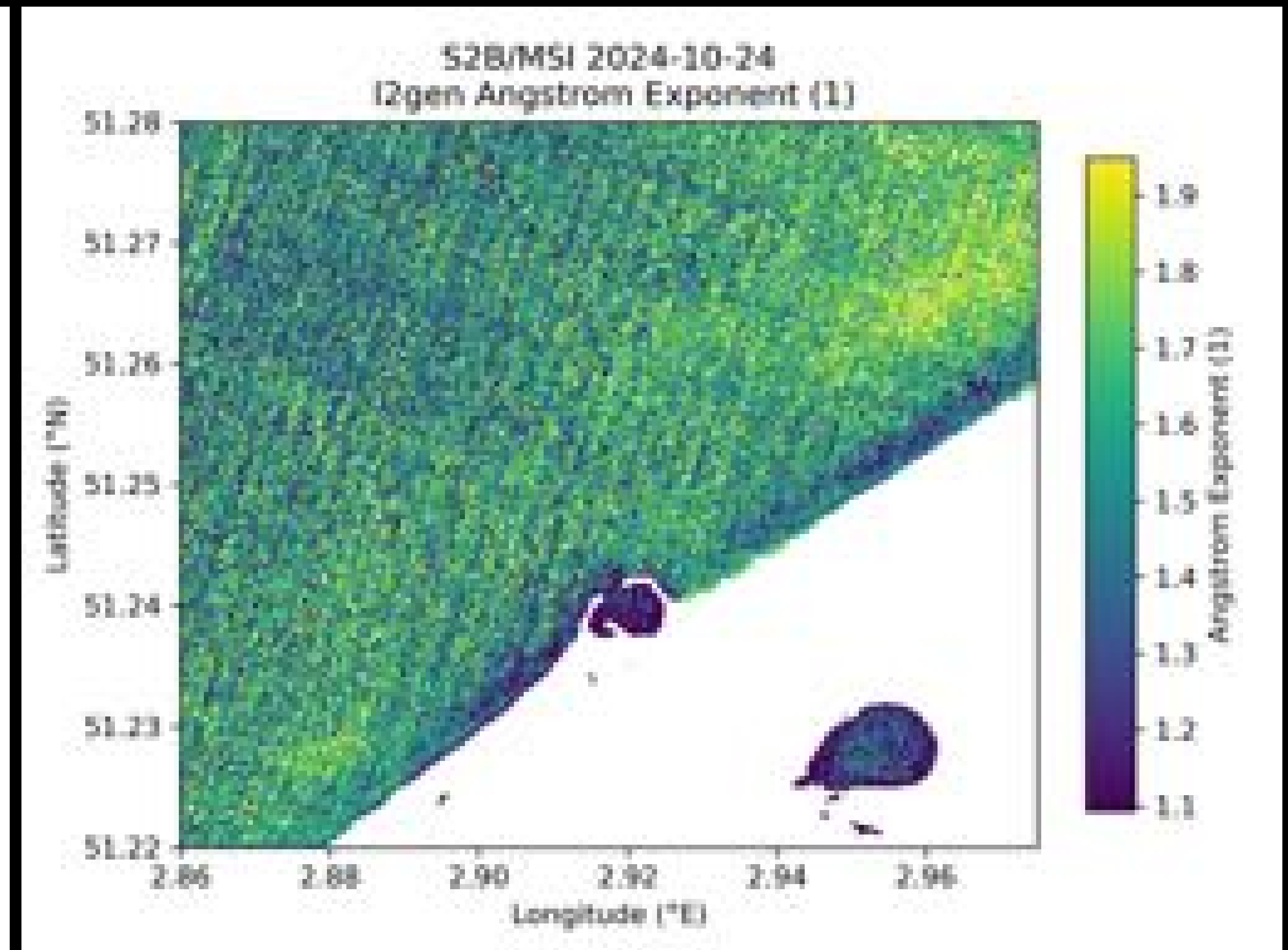


aerosol optical depth ~ increase towards shore, in port and lake

I2gen

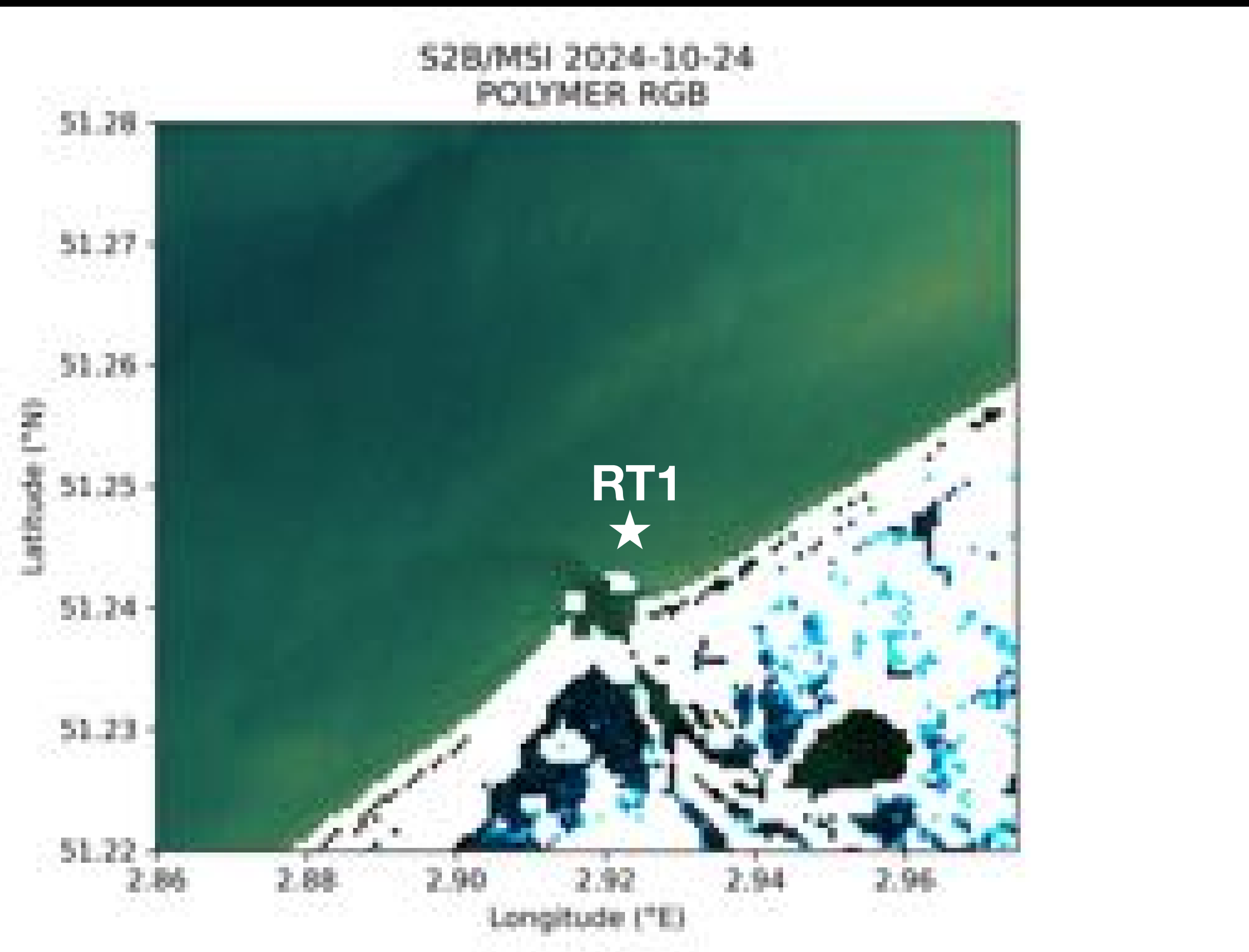


noisy aerosol products -> noisy Rrs

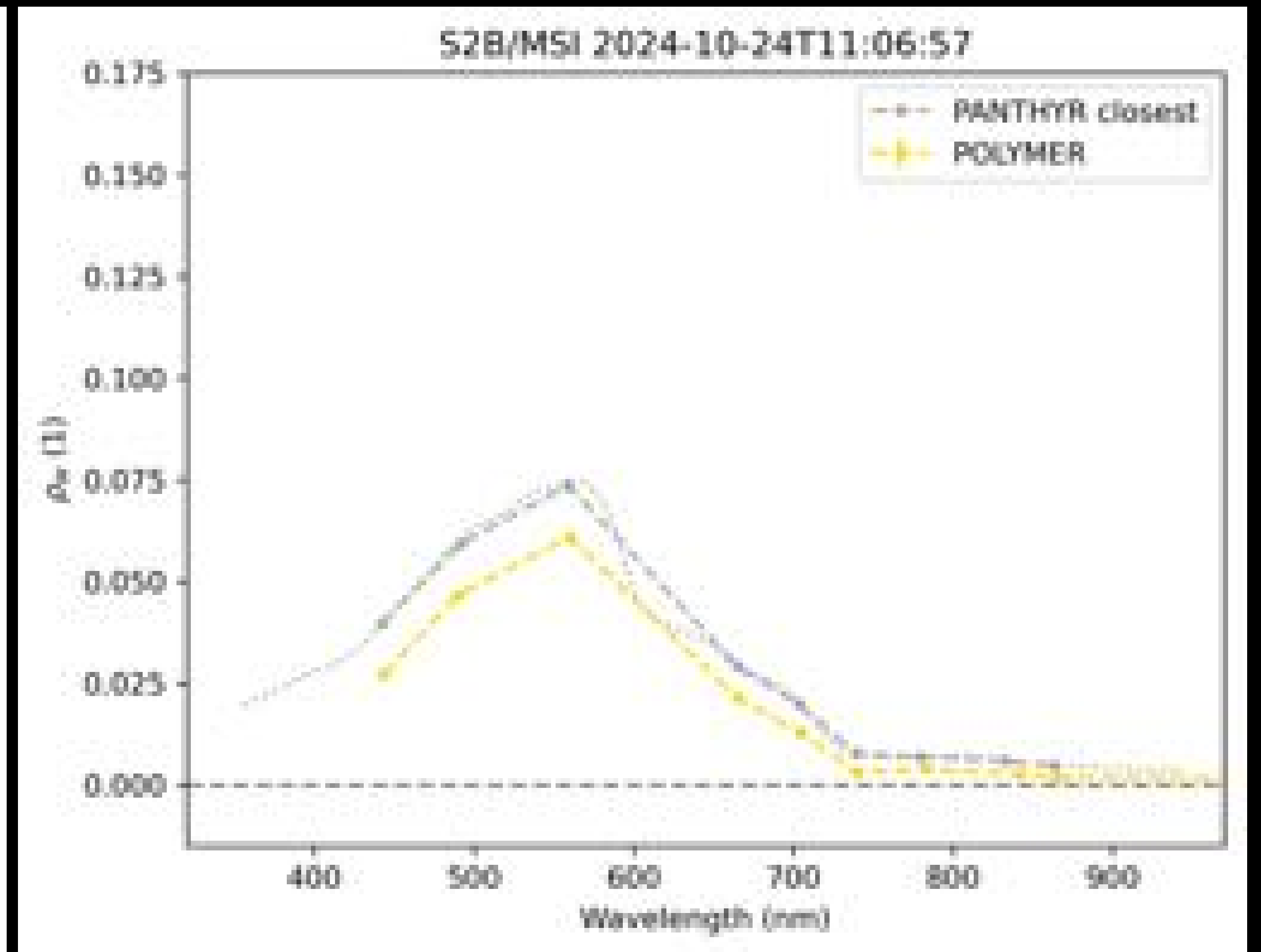


Angstrom ~ water turbidity, port and lake have low angstrom

POLYMER

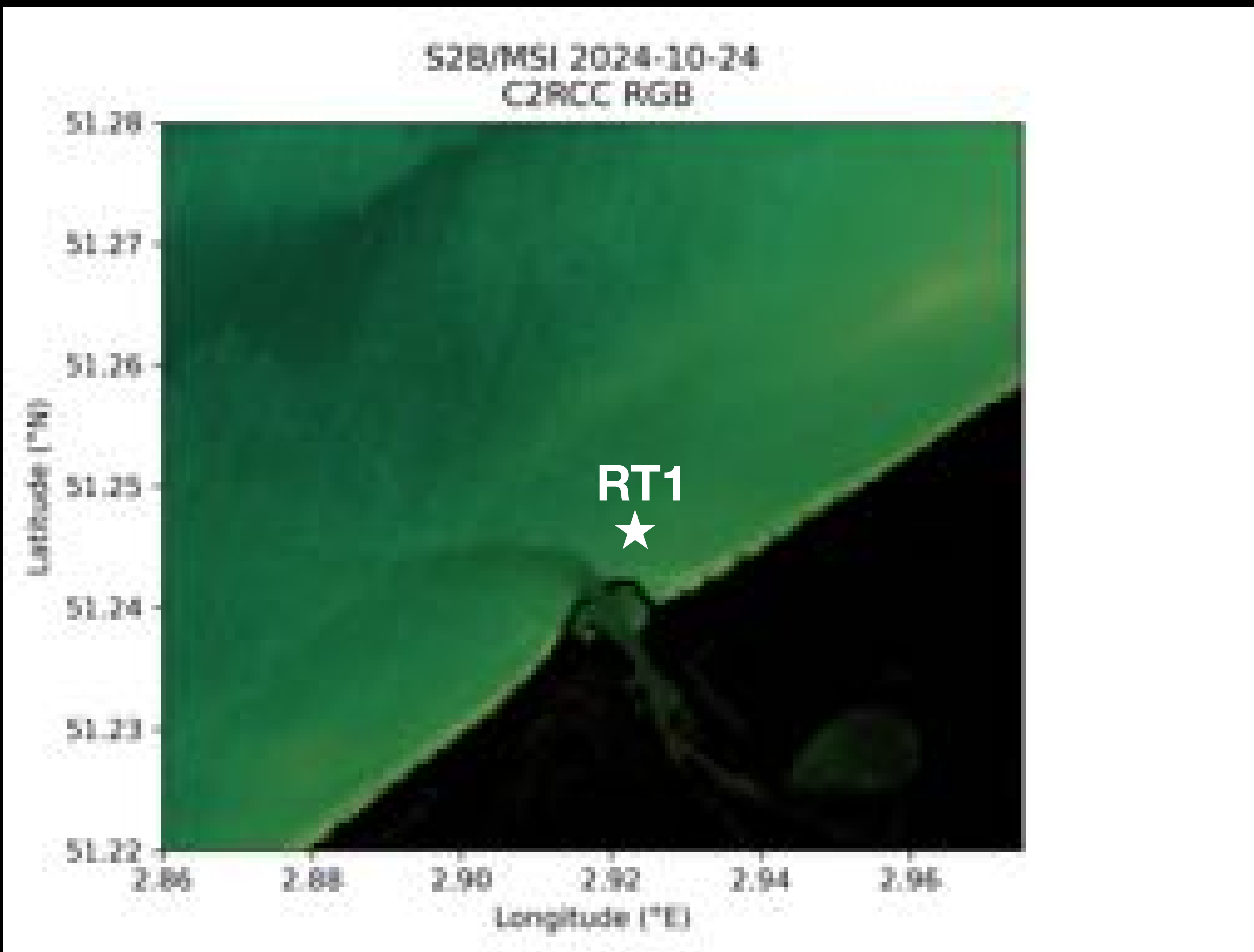


similar colour compared to I2gen, slightly noisier, but no failures

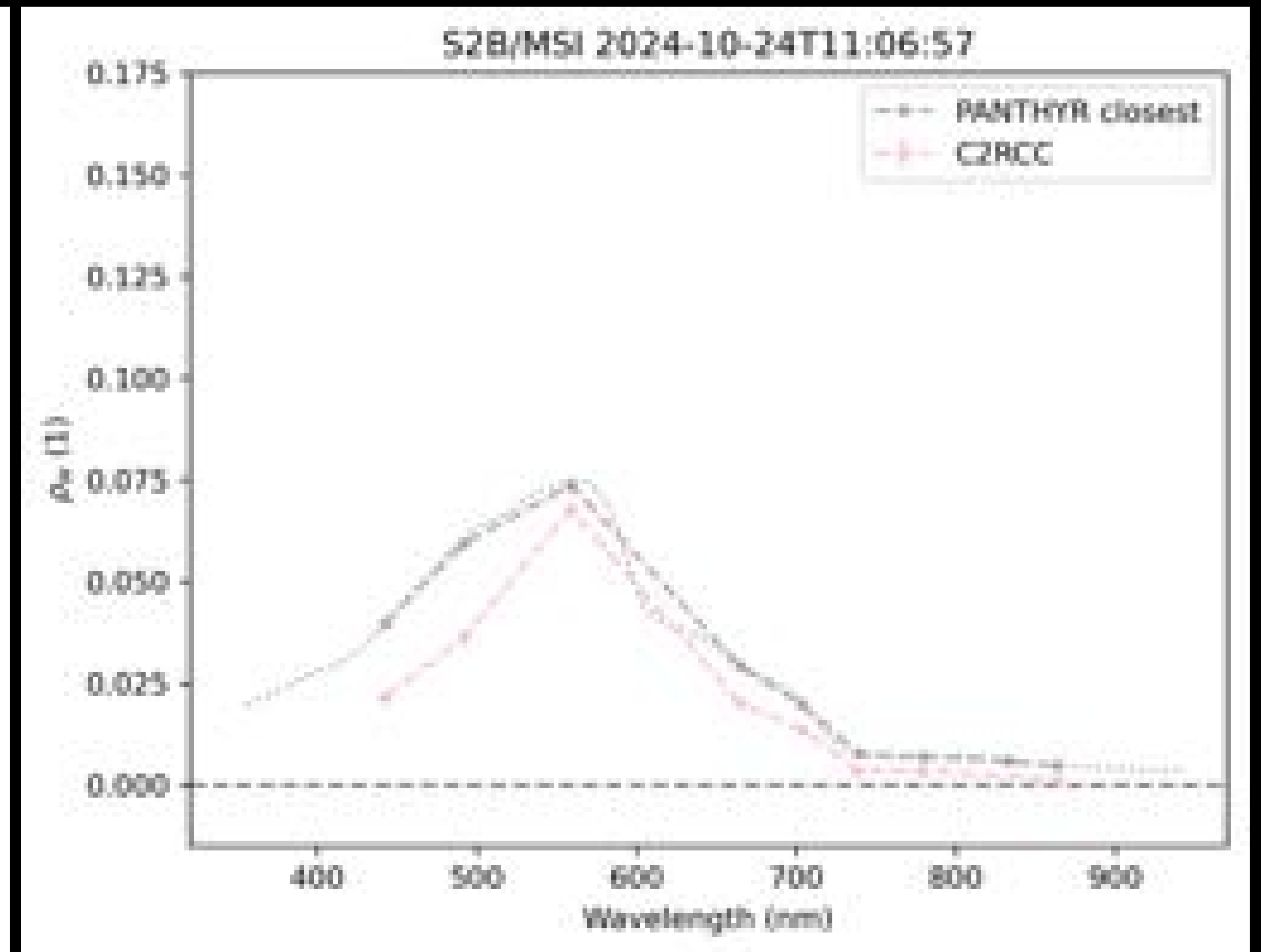


overcorrection, slightly brighter compared to I2gen

C2RCC

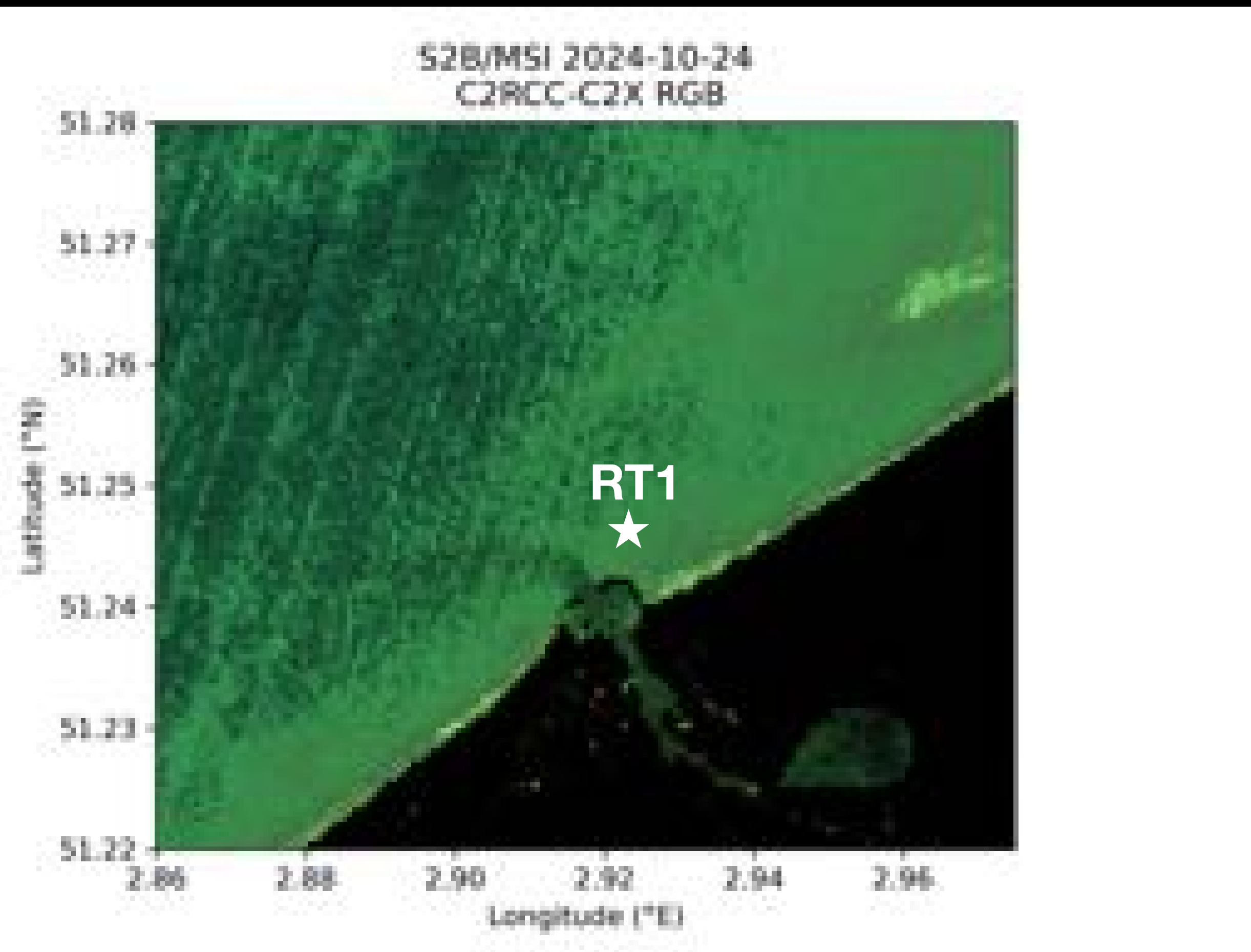


a bit brighter than I2gen/POLYMER, greener appearance

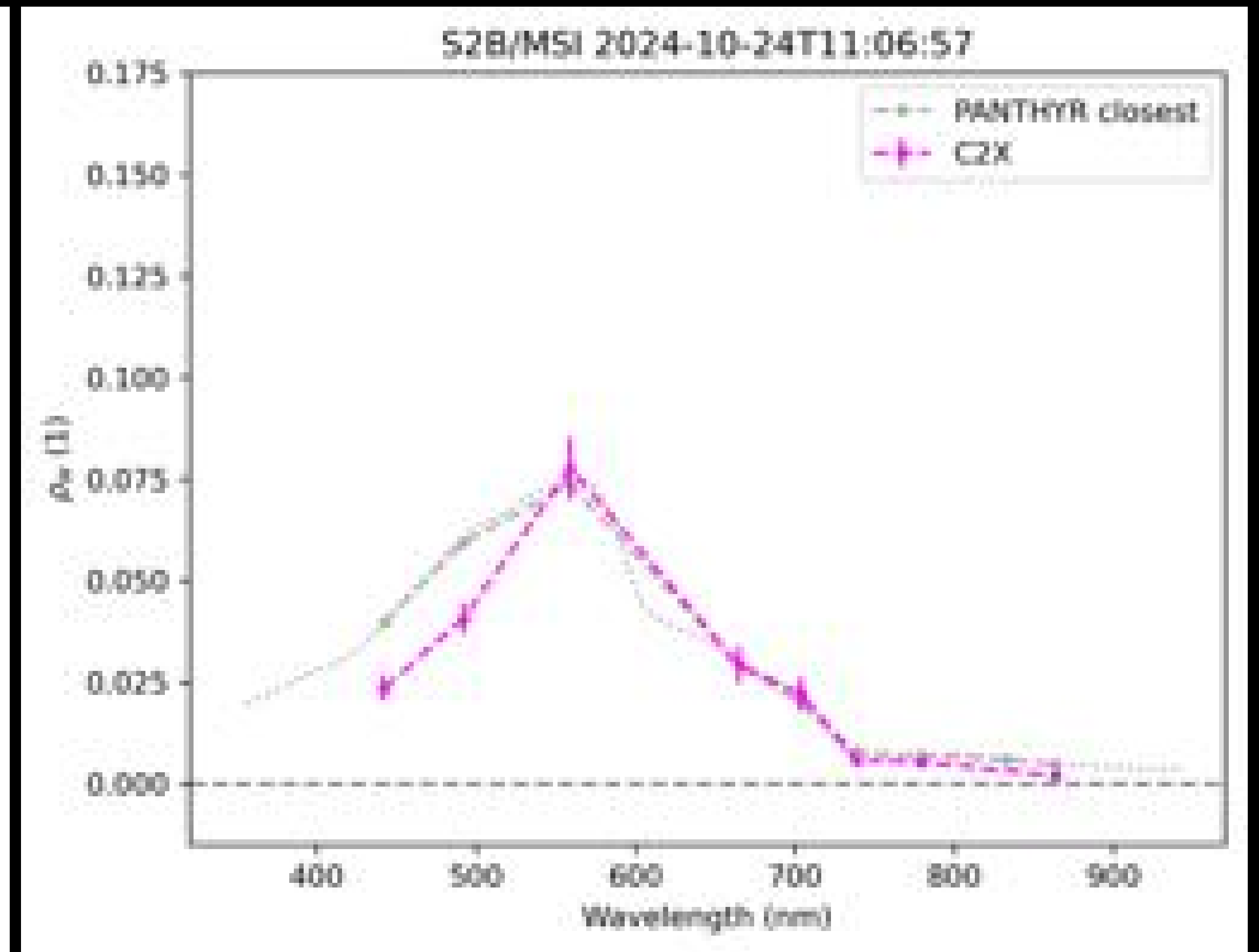


higher reflectance than I2gen/POLYMER, difference in blue shape

C2RCC-C2X

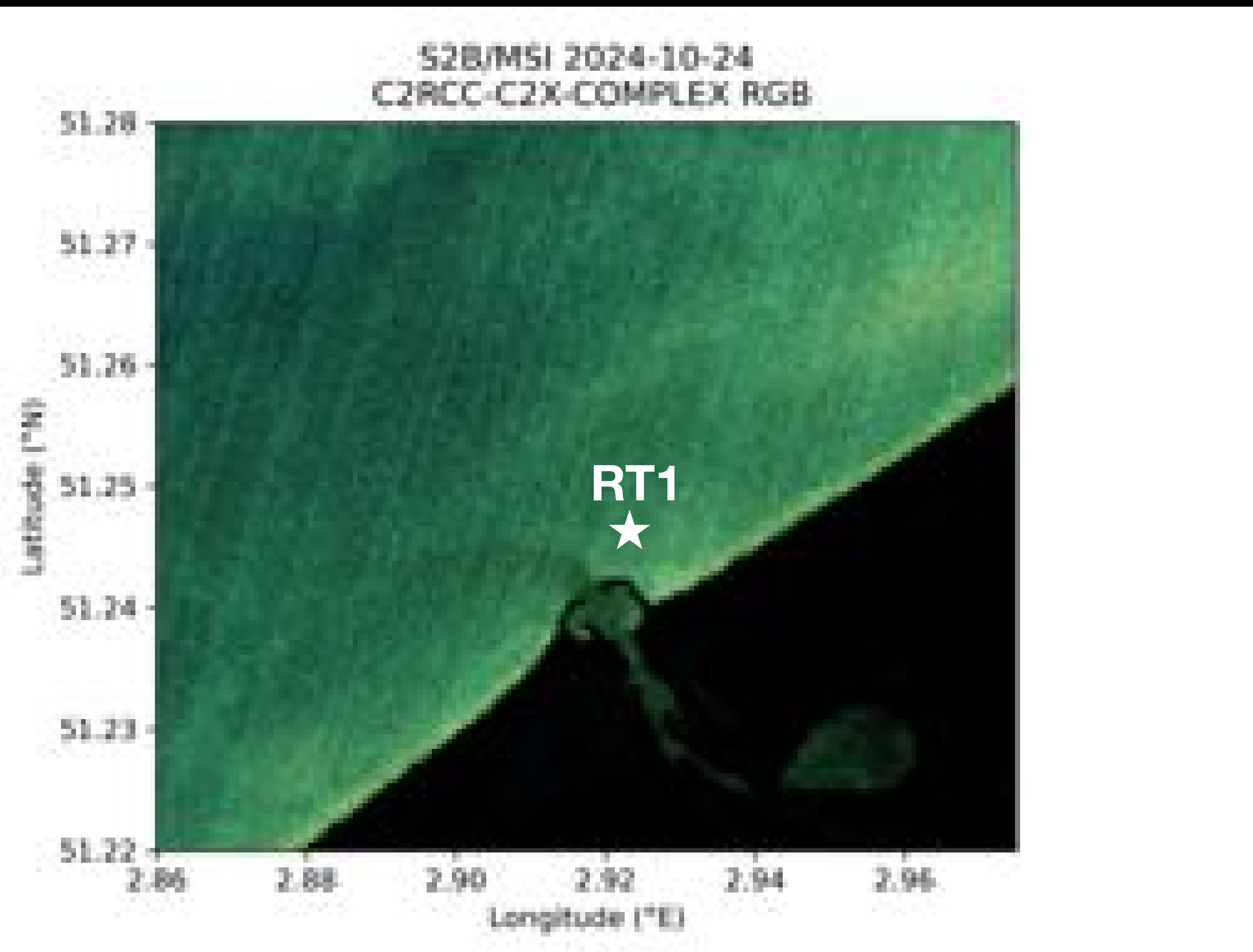


a bit brighter than C2RCC, more noise, spatial variability reduced

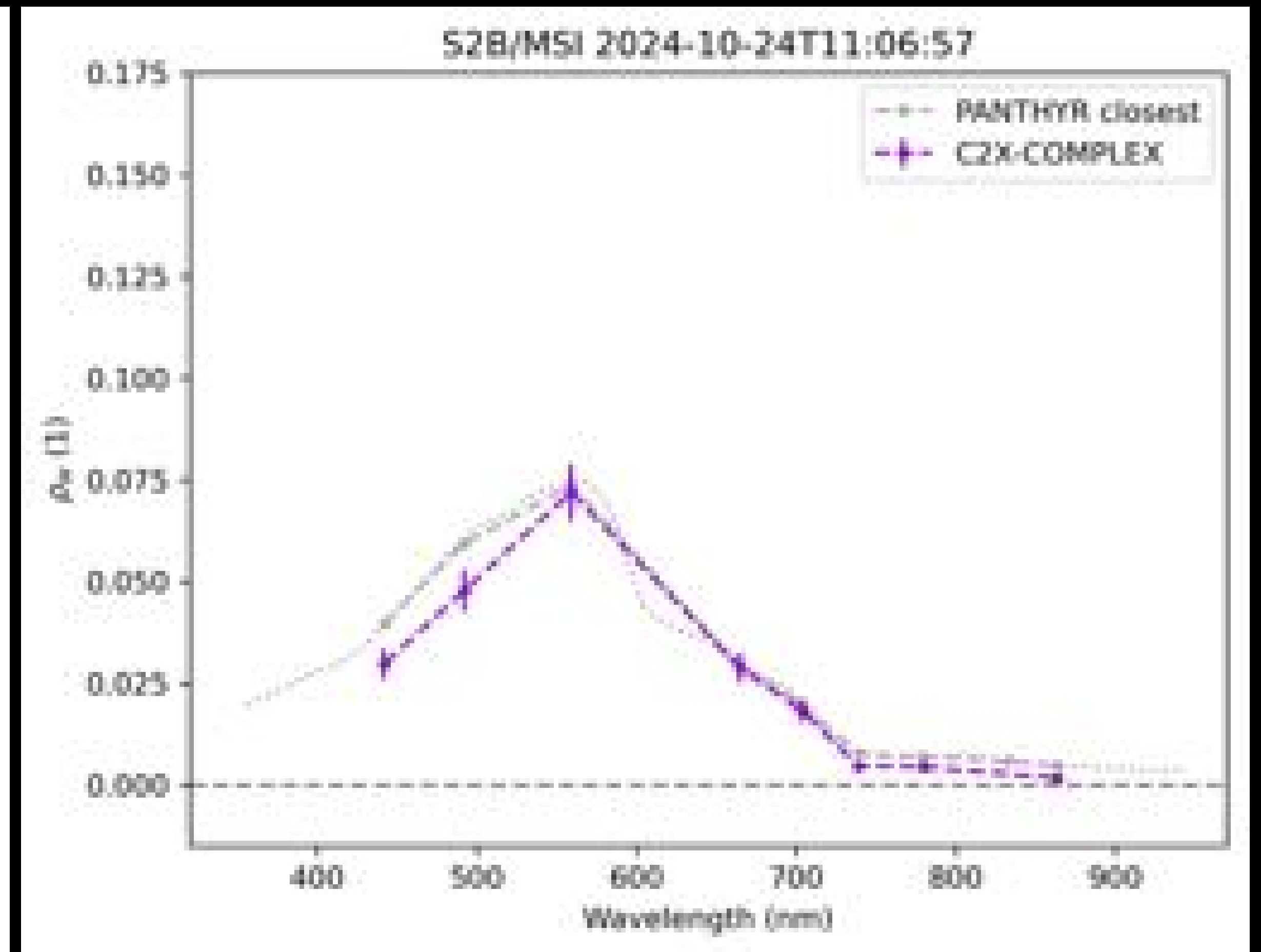


better fit compared to C2RCC in green-NIR

C2RCC-COMPLEX

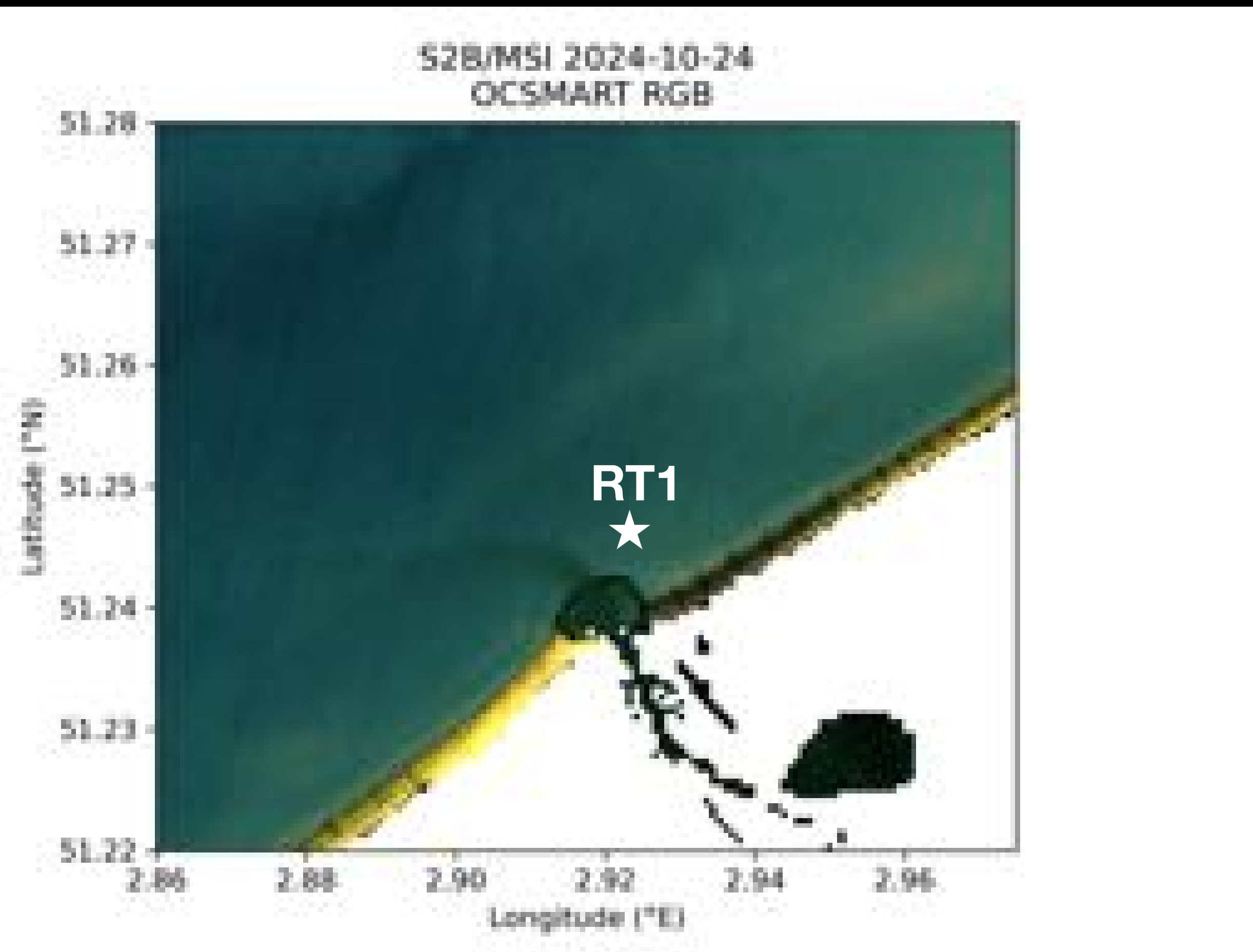


a bit brighter than C2RCC, more noise, spatial variability reduced

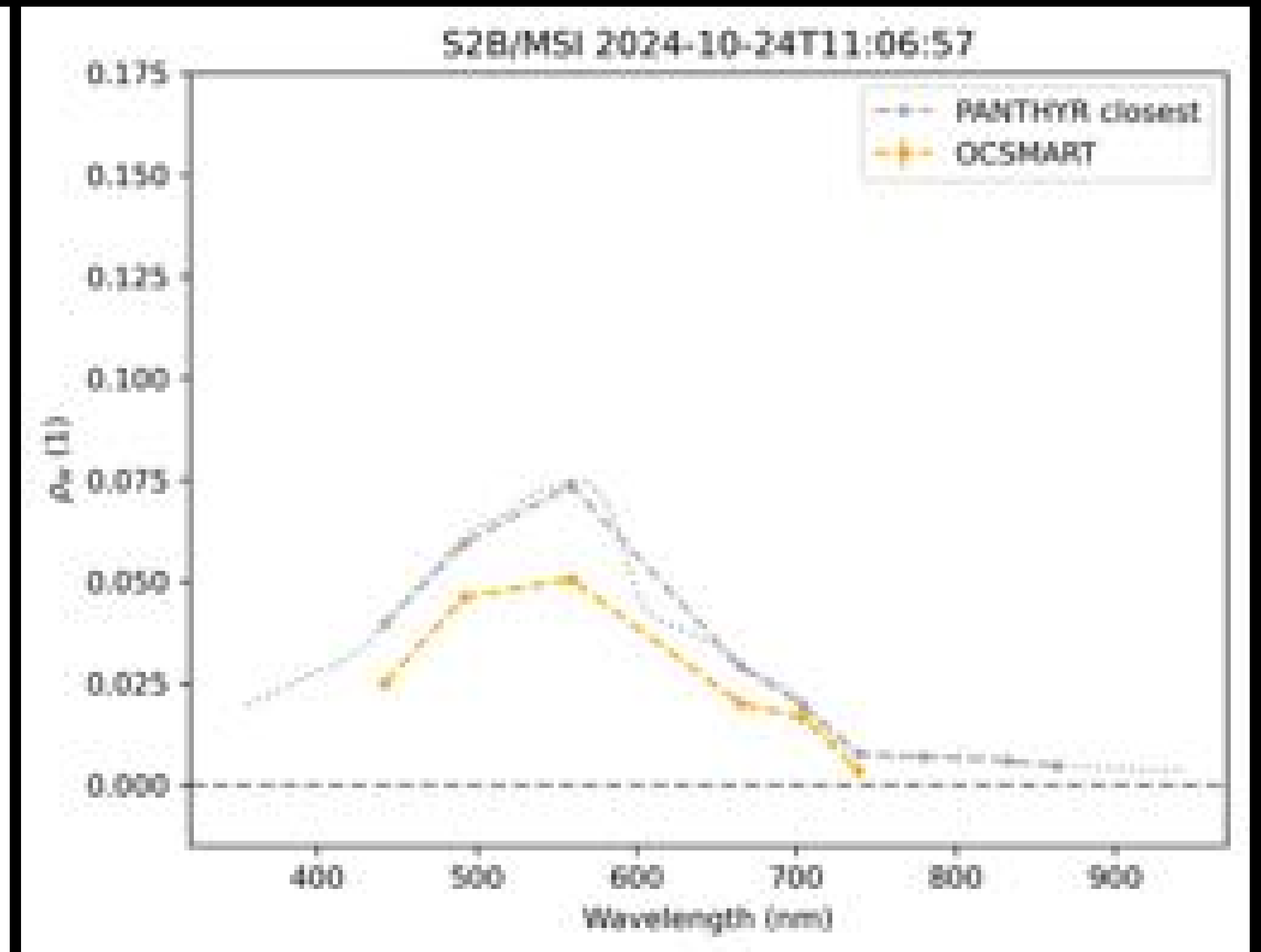


better fit compared to C2RCC and C2X, slight under-correction in Blue

OC-SMART

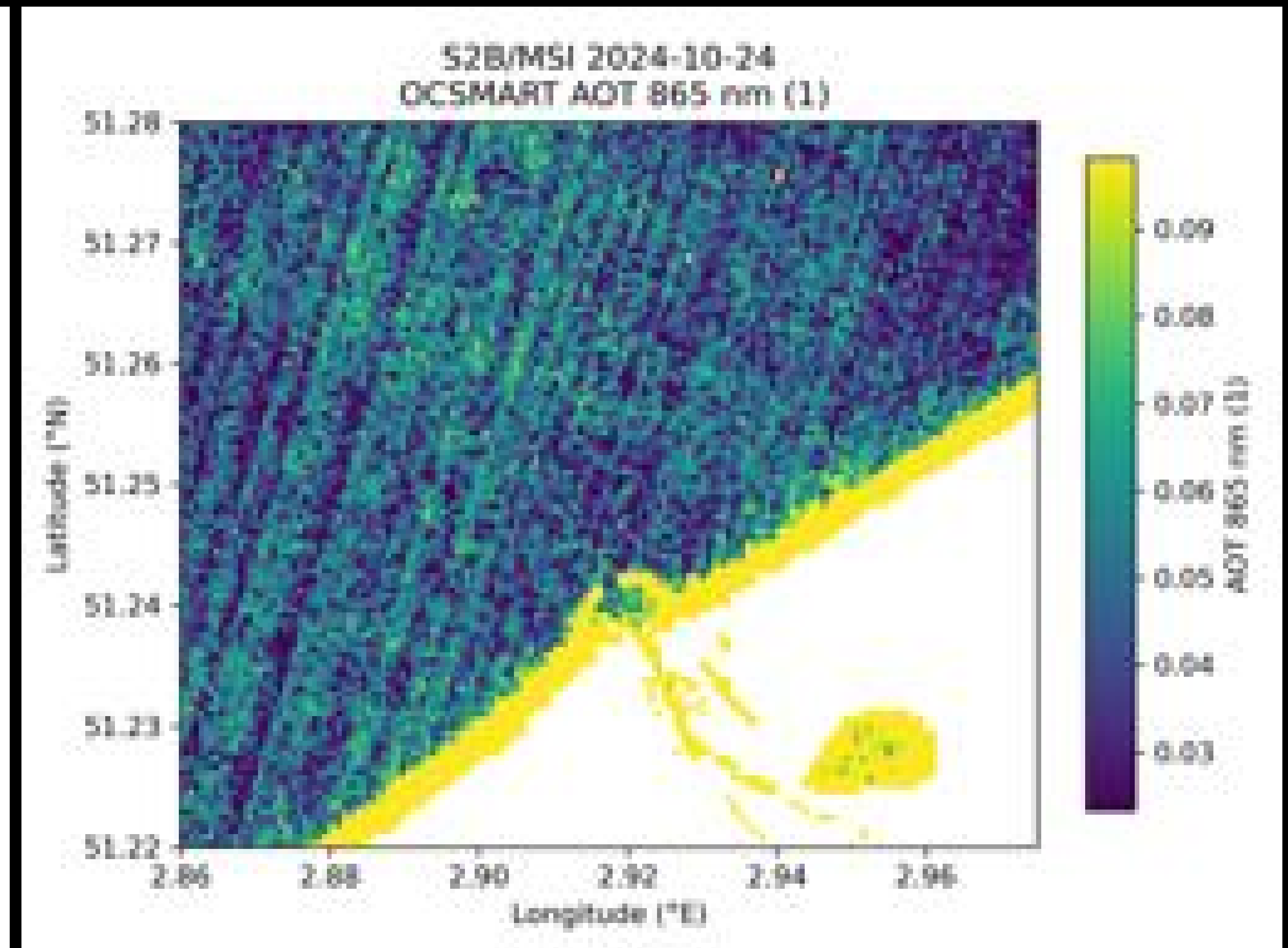
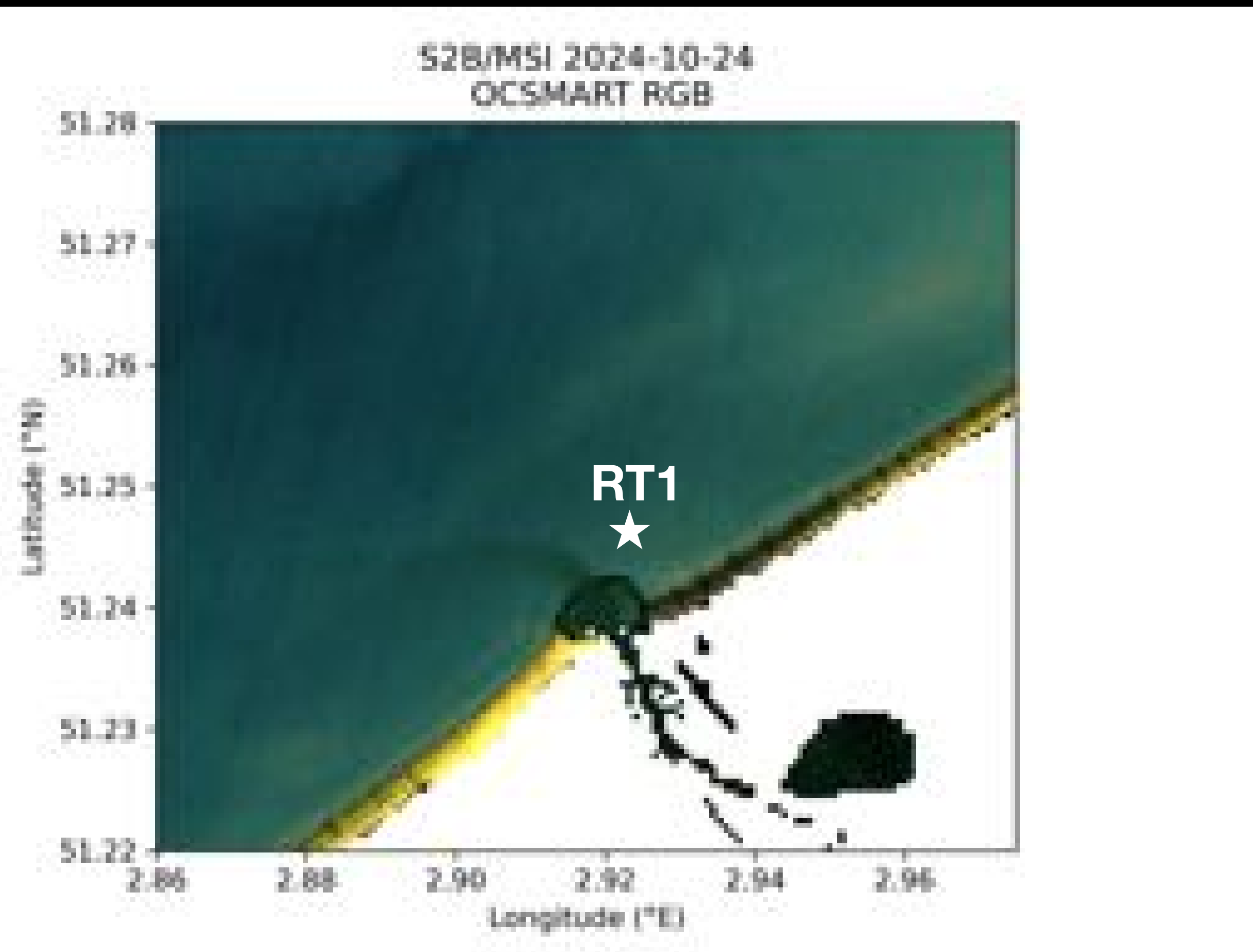


lower reflectance, a bit less green



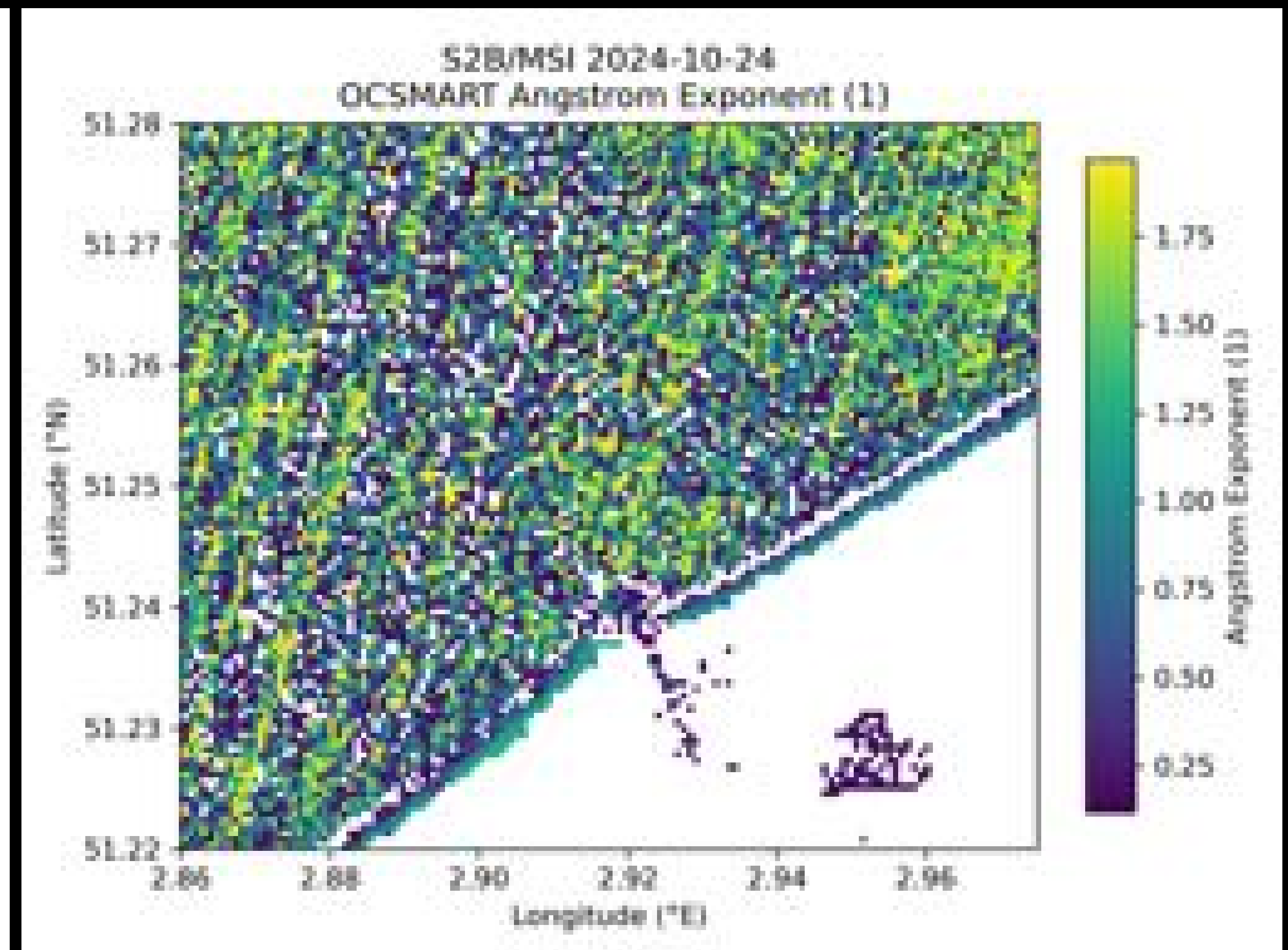
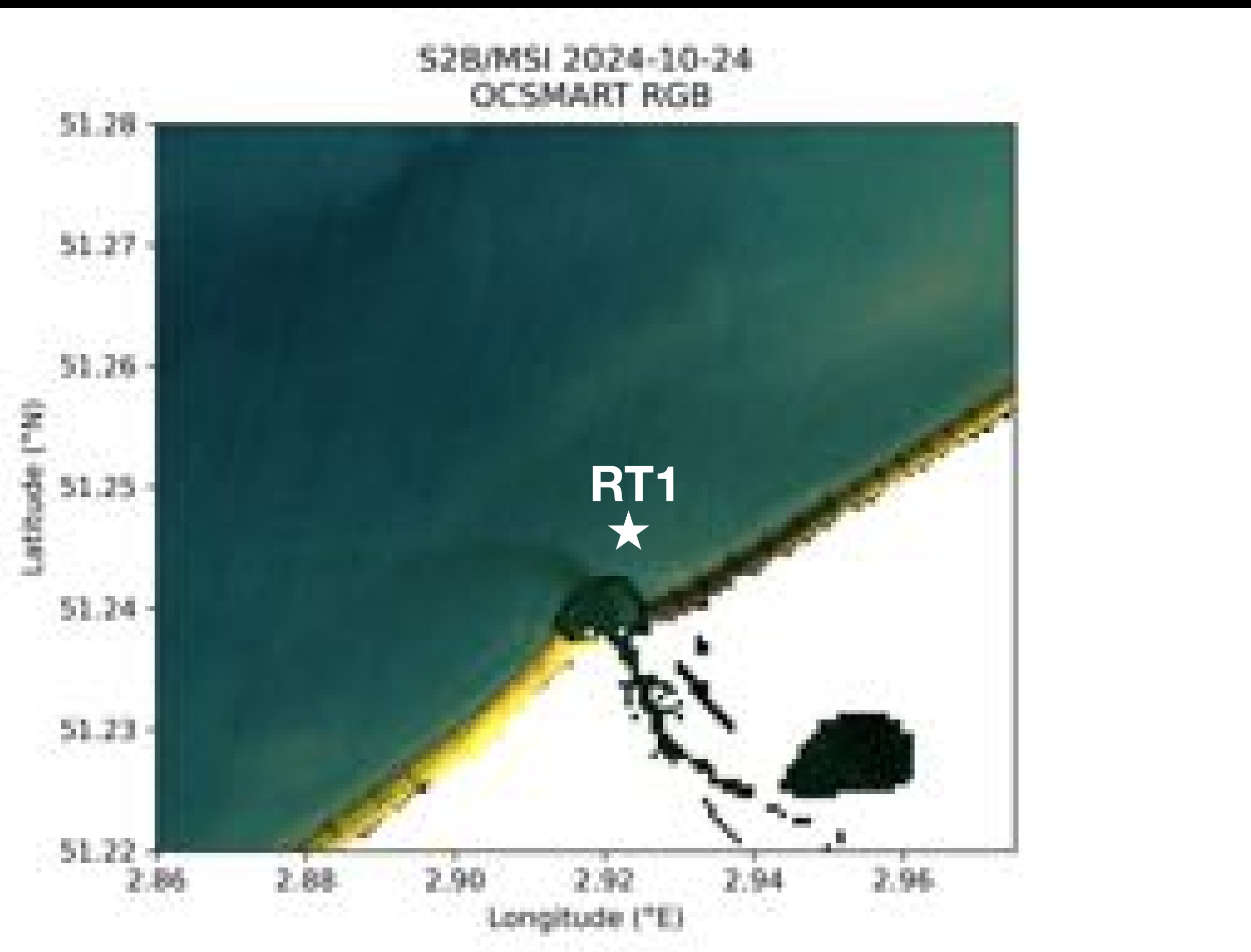
overcorrection in VIS, slight red absorption feature introduced

OC-SMART



aerosol optical depth ~ noisy, high in the port and lake

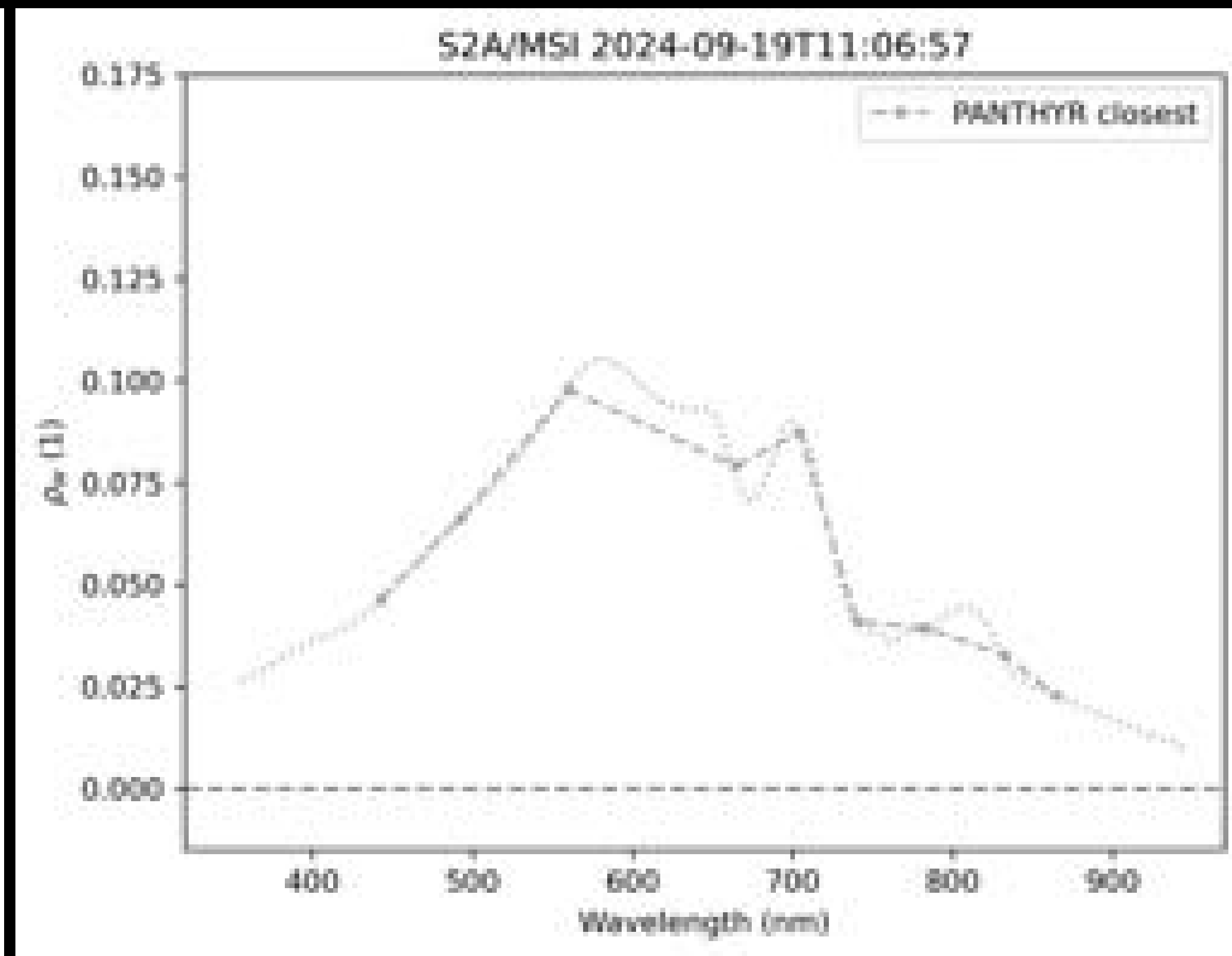
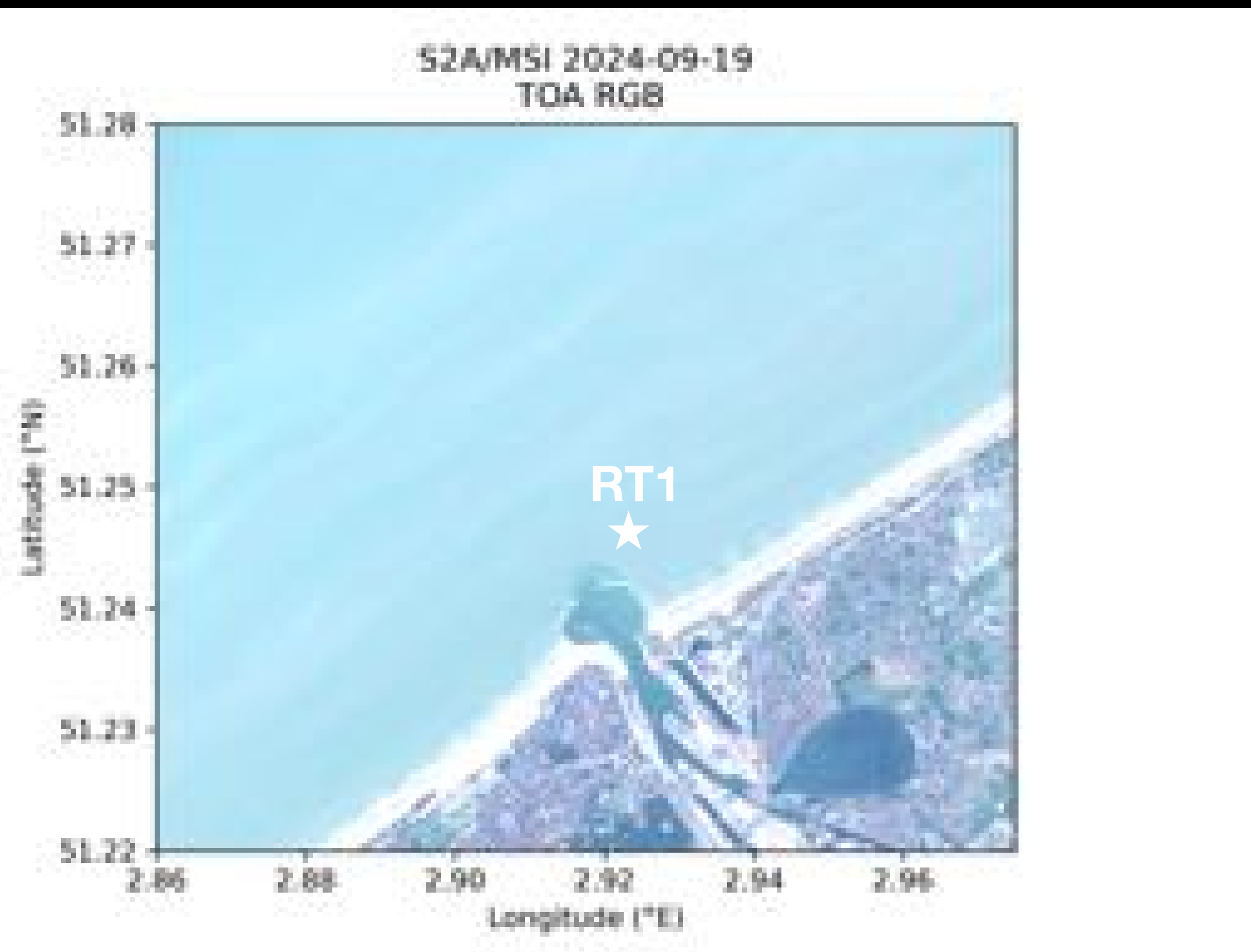
OC-SMART



Angstrom ~ noisy!

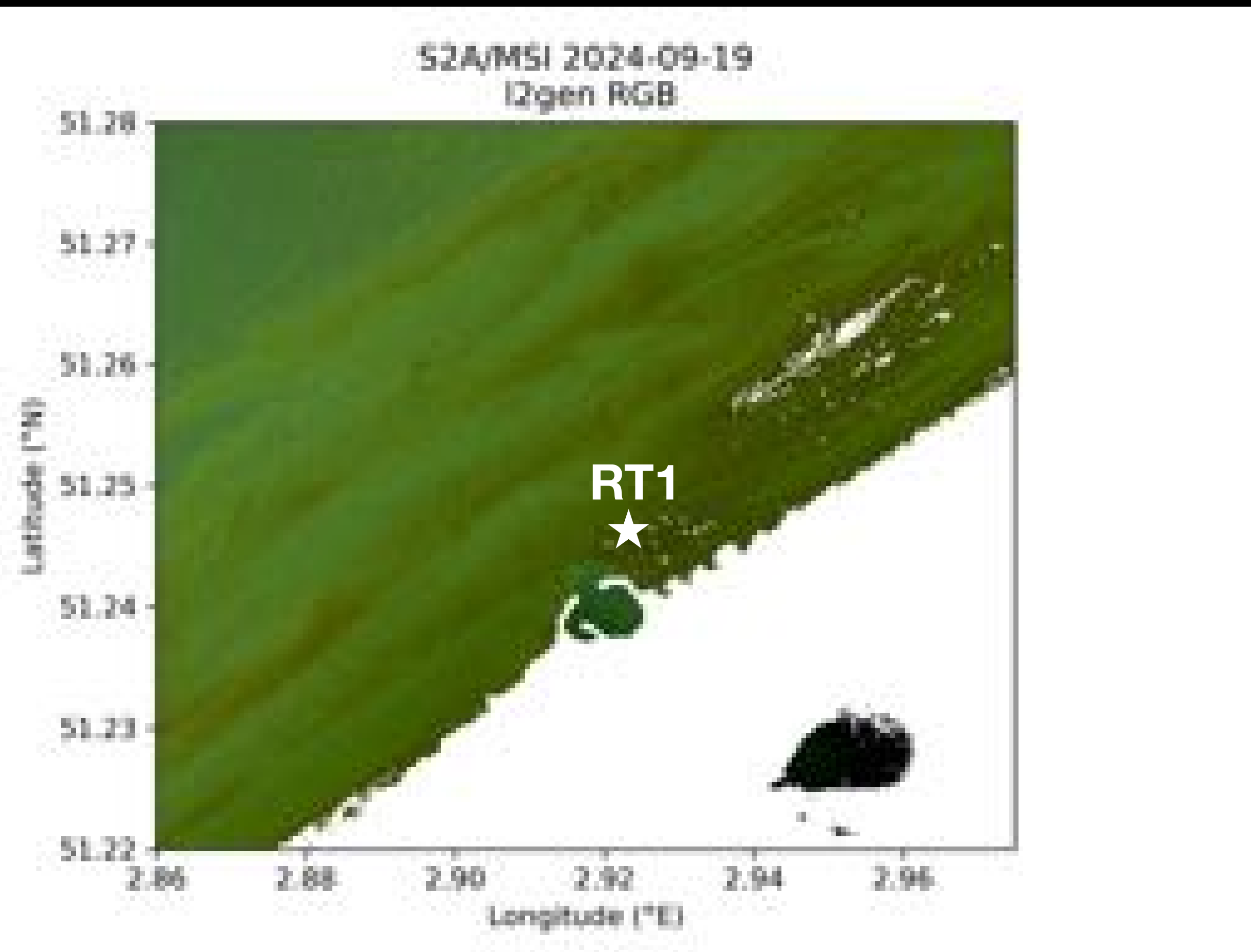
TOA 2024-09-19

PANTHYR

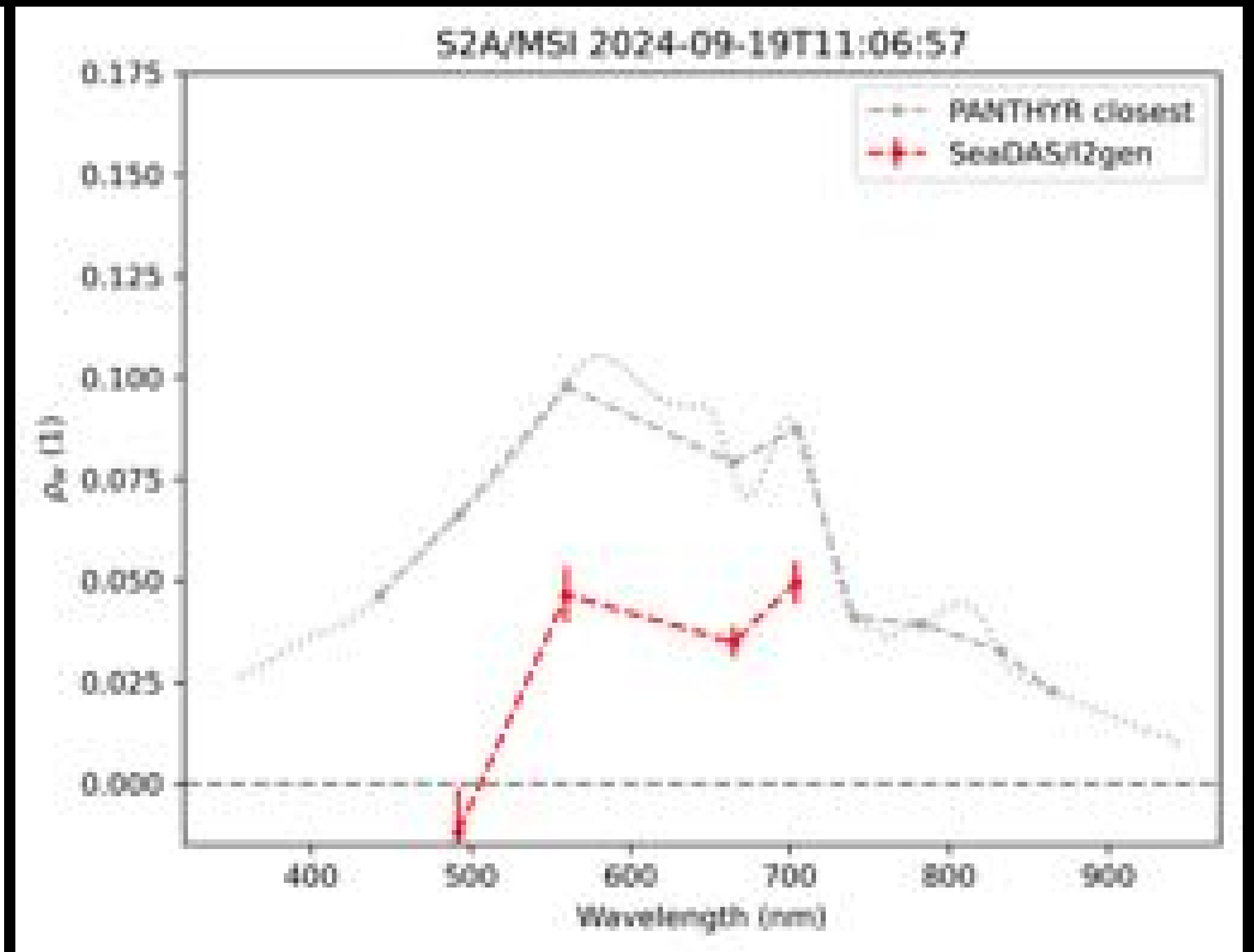


quite turbid, some Chla (665 nm dip)

I2gen

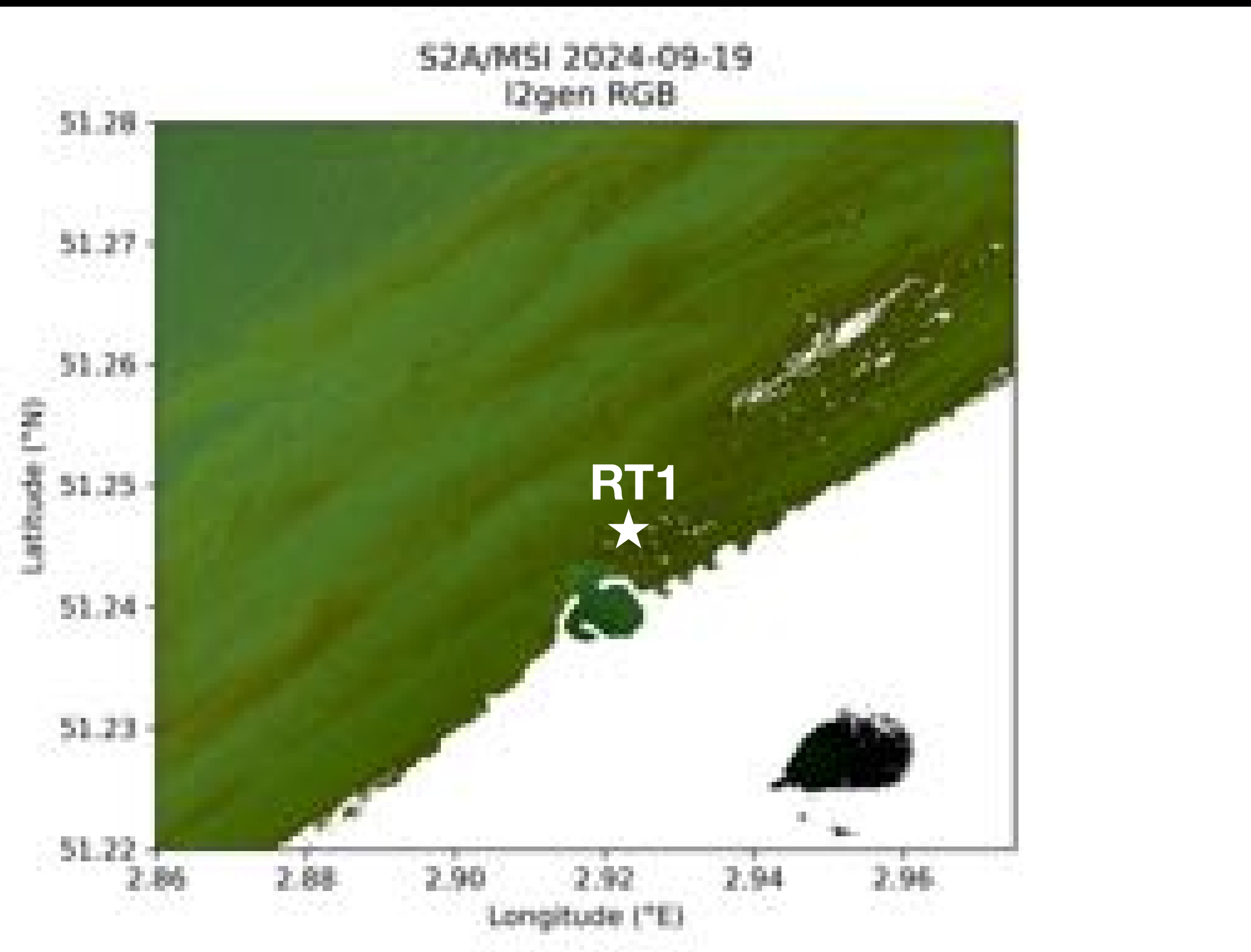


greenish appearance, more turbid ~ more red/brown,
some pixels masked (Blue $\ll 0$)

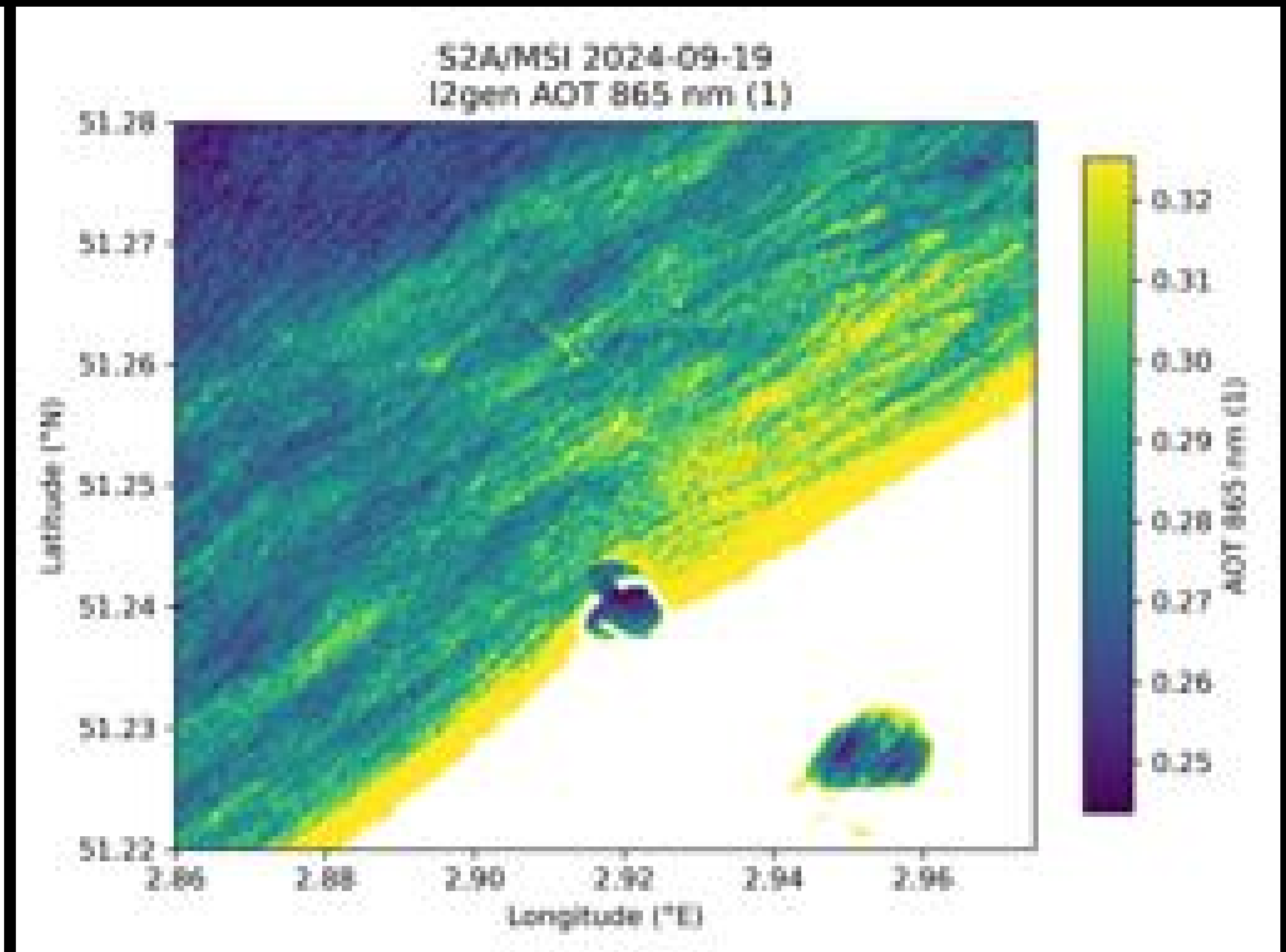


overcorrection, especially in Blue

I2gen

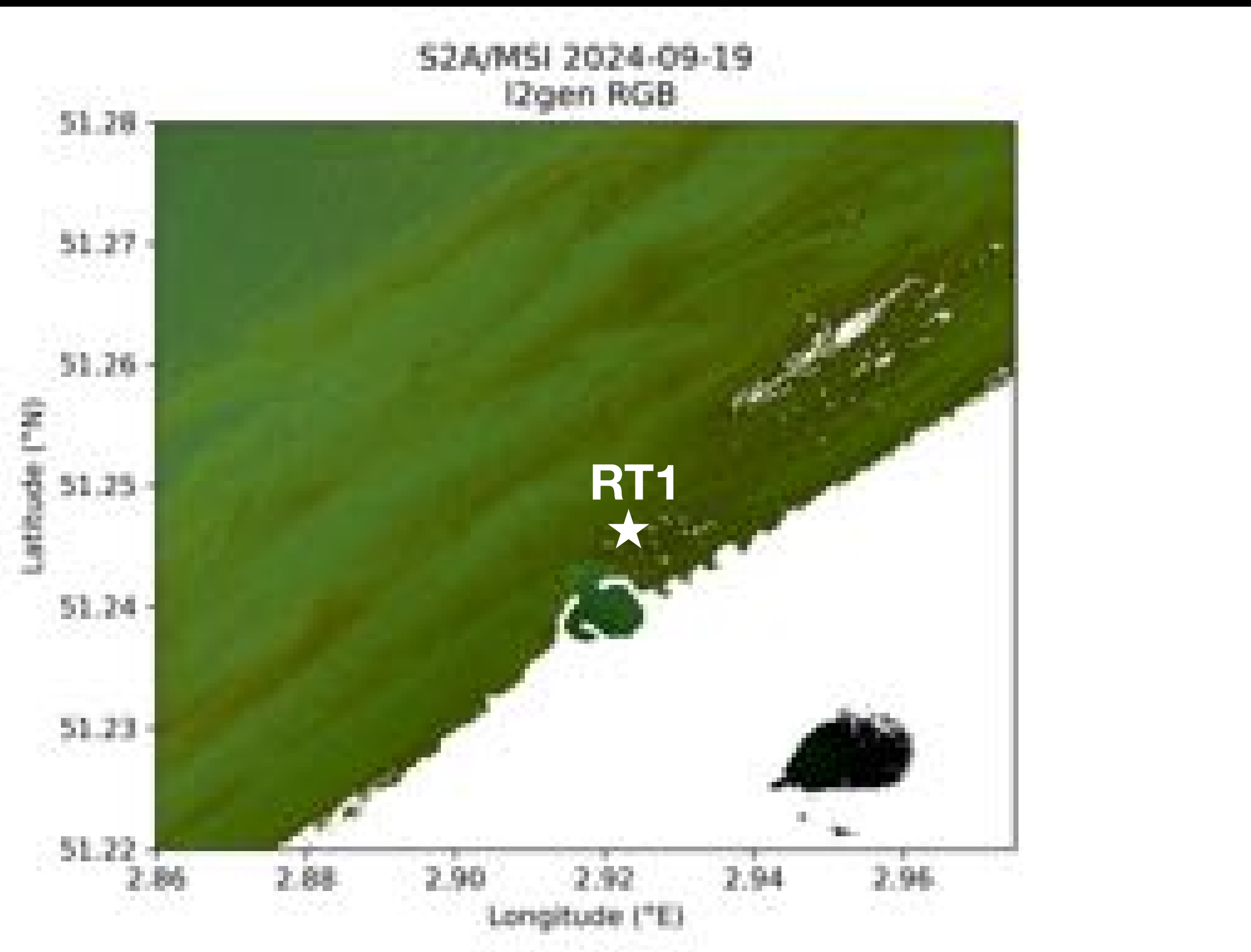


masking (blue band $\ll 0$) ~ high aerosol optical depth

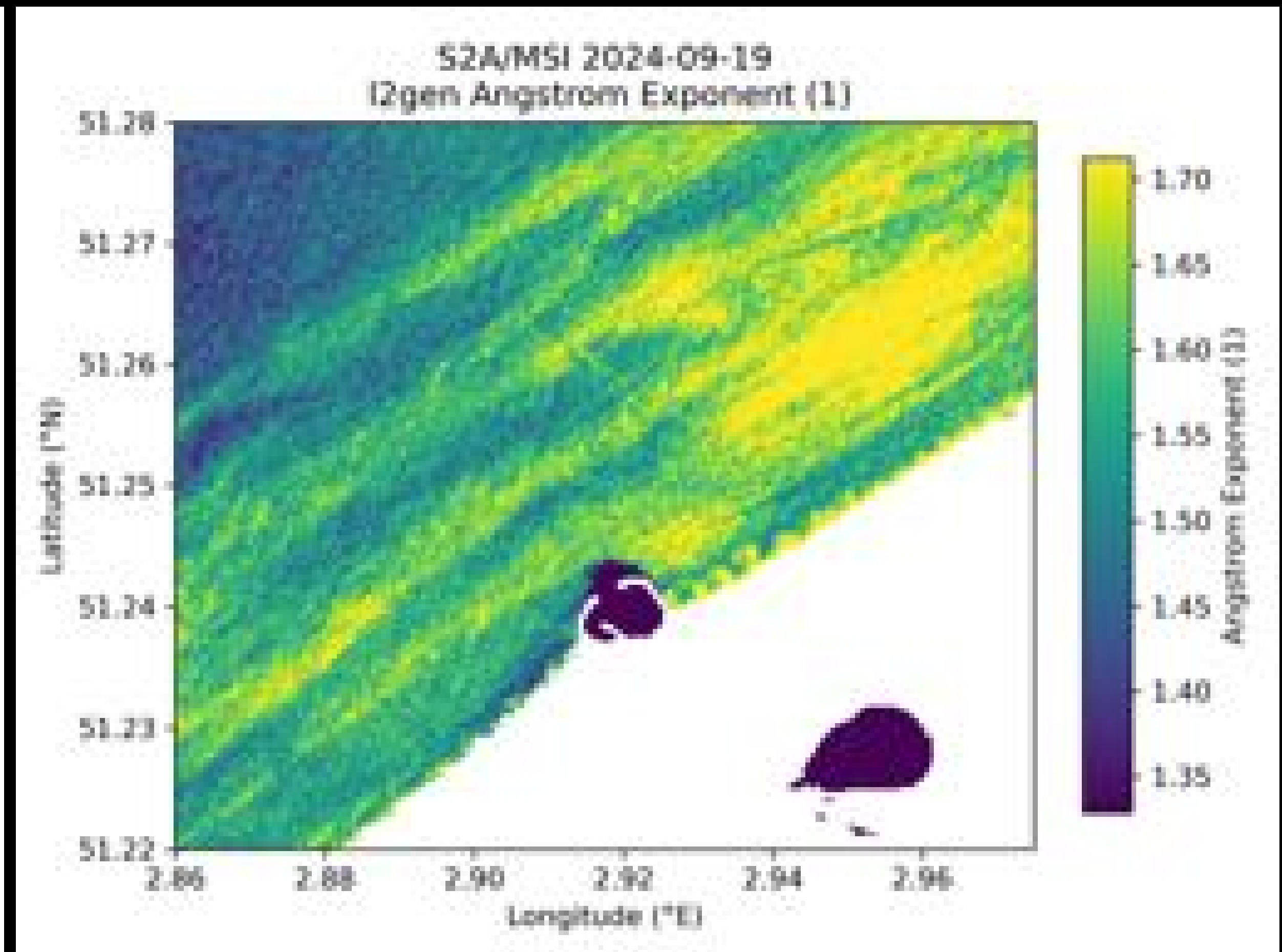


aerosol optical depth ~ water turbidity

I2gen

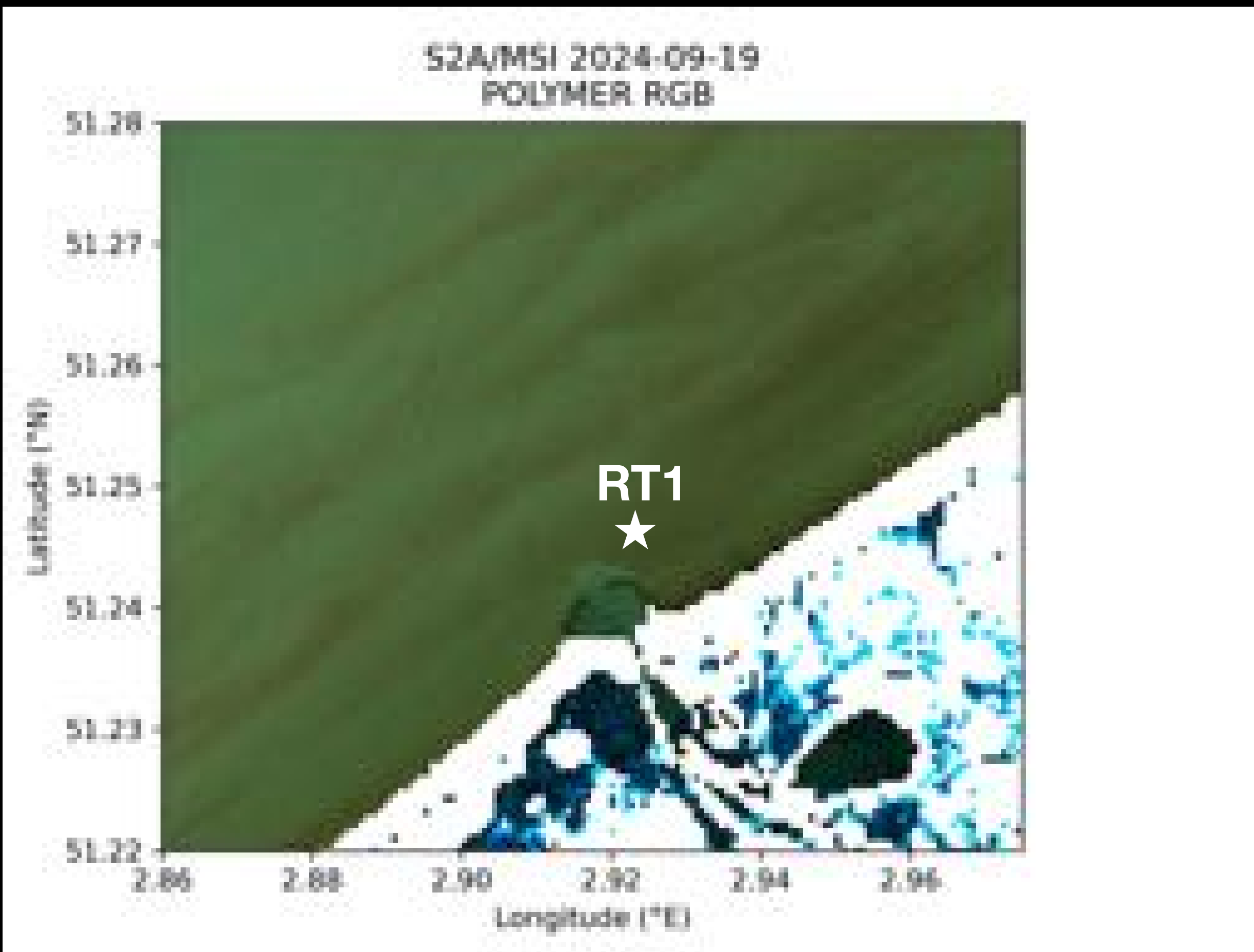


masking (blue band $\ll 0$) ~ high aerosol Angstrom

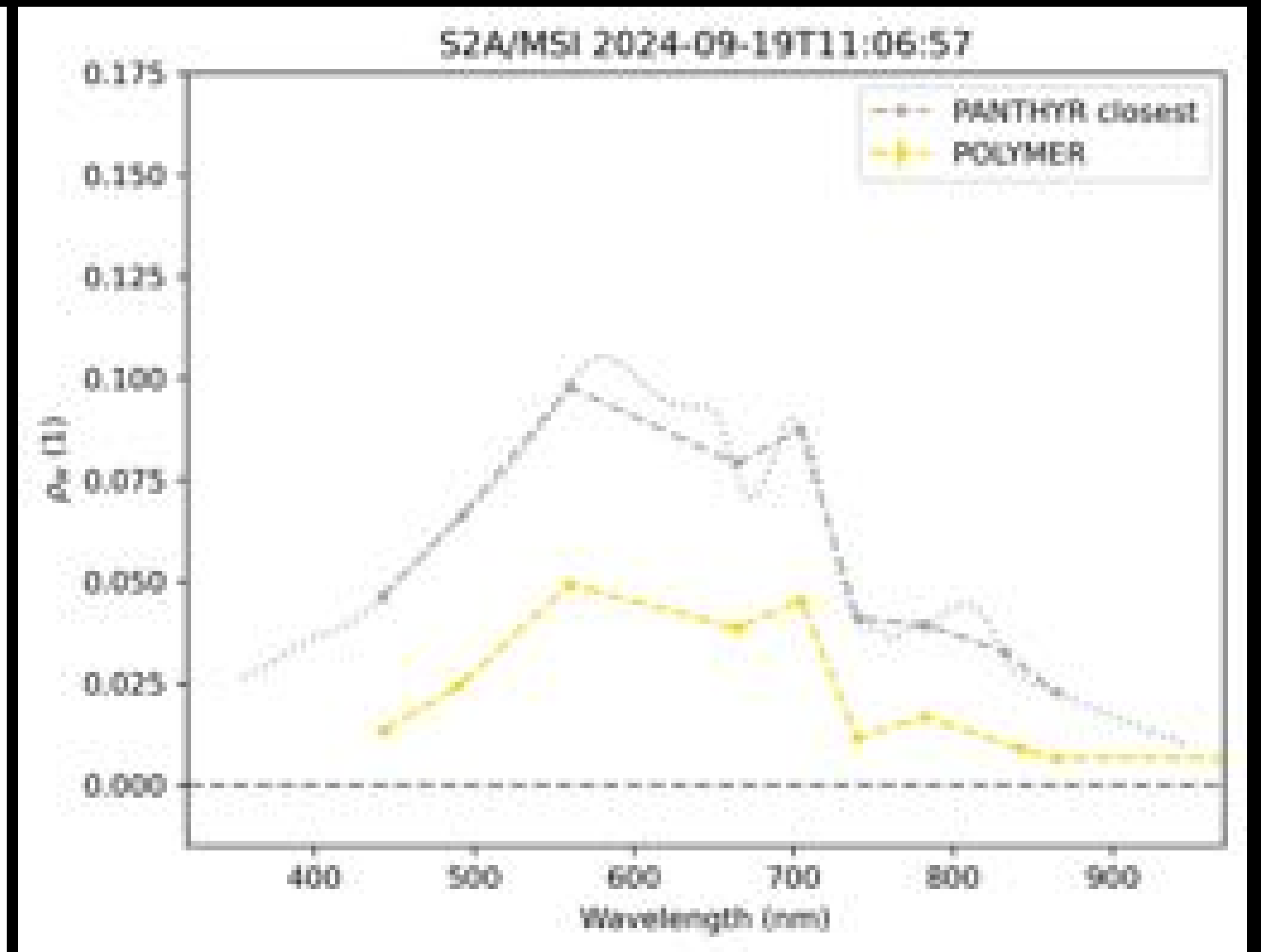


Angstrom ~ water turbidity, port and lake have low angstrom

POLYMER

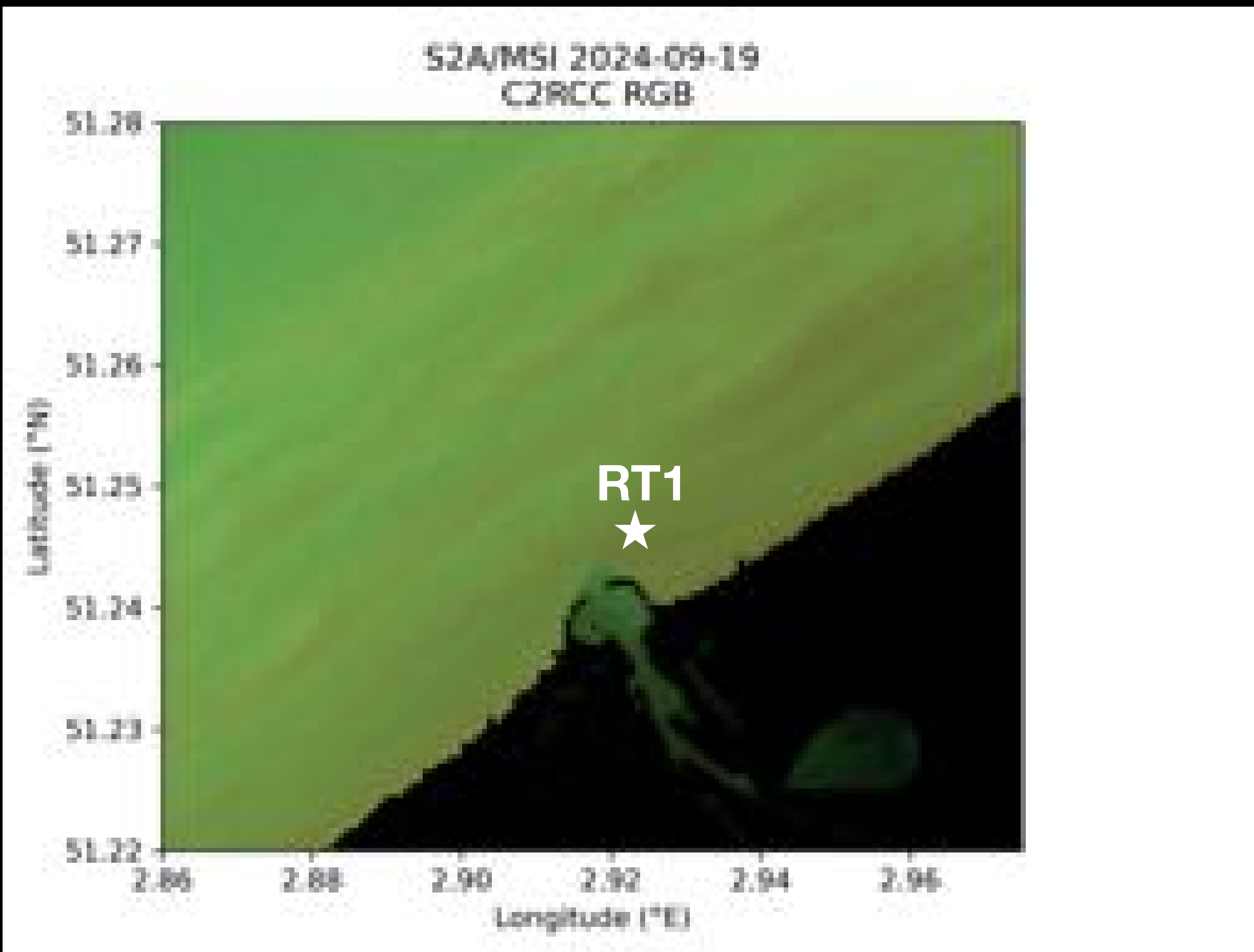


less green and a bit darker than I2gen, brown over most turbid areas

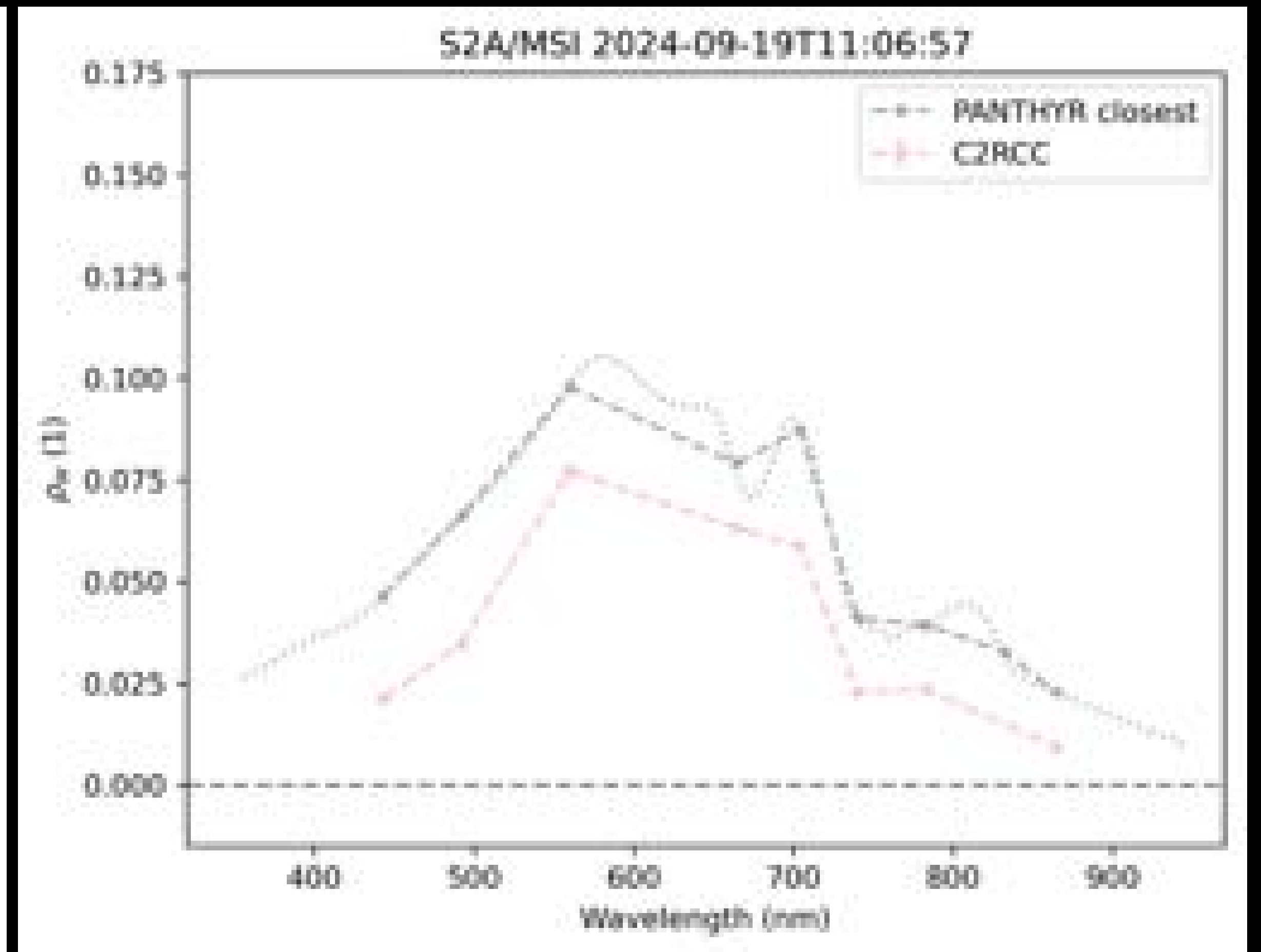


overcorrection, more flat compared to I2gen

C2RCC

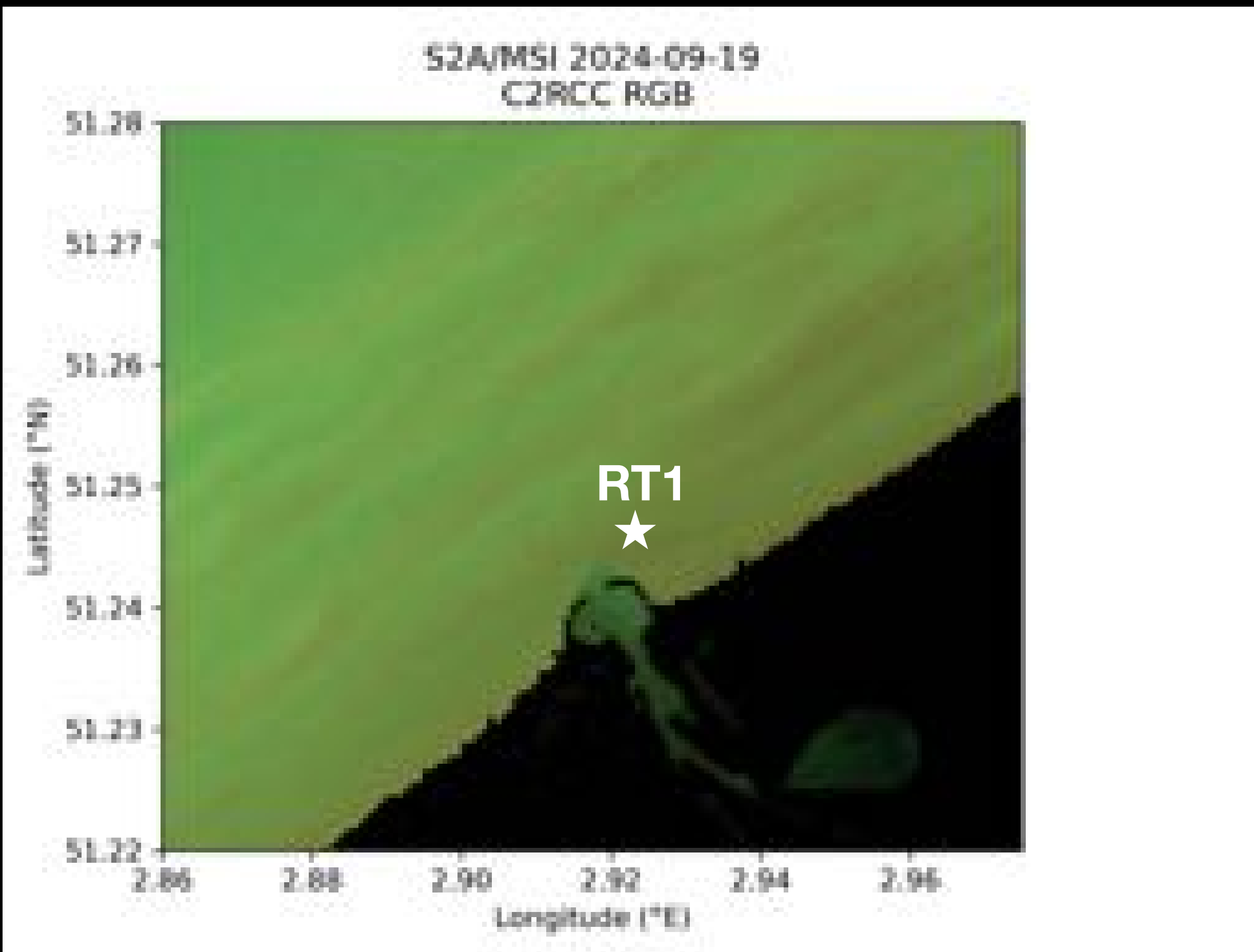


a bit brighter than I2gen/POLYMER, brown over most turbid areas

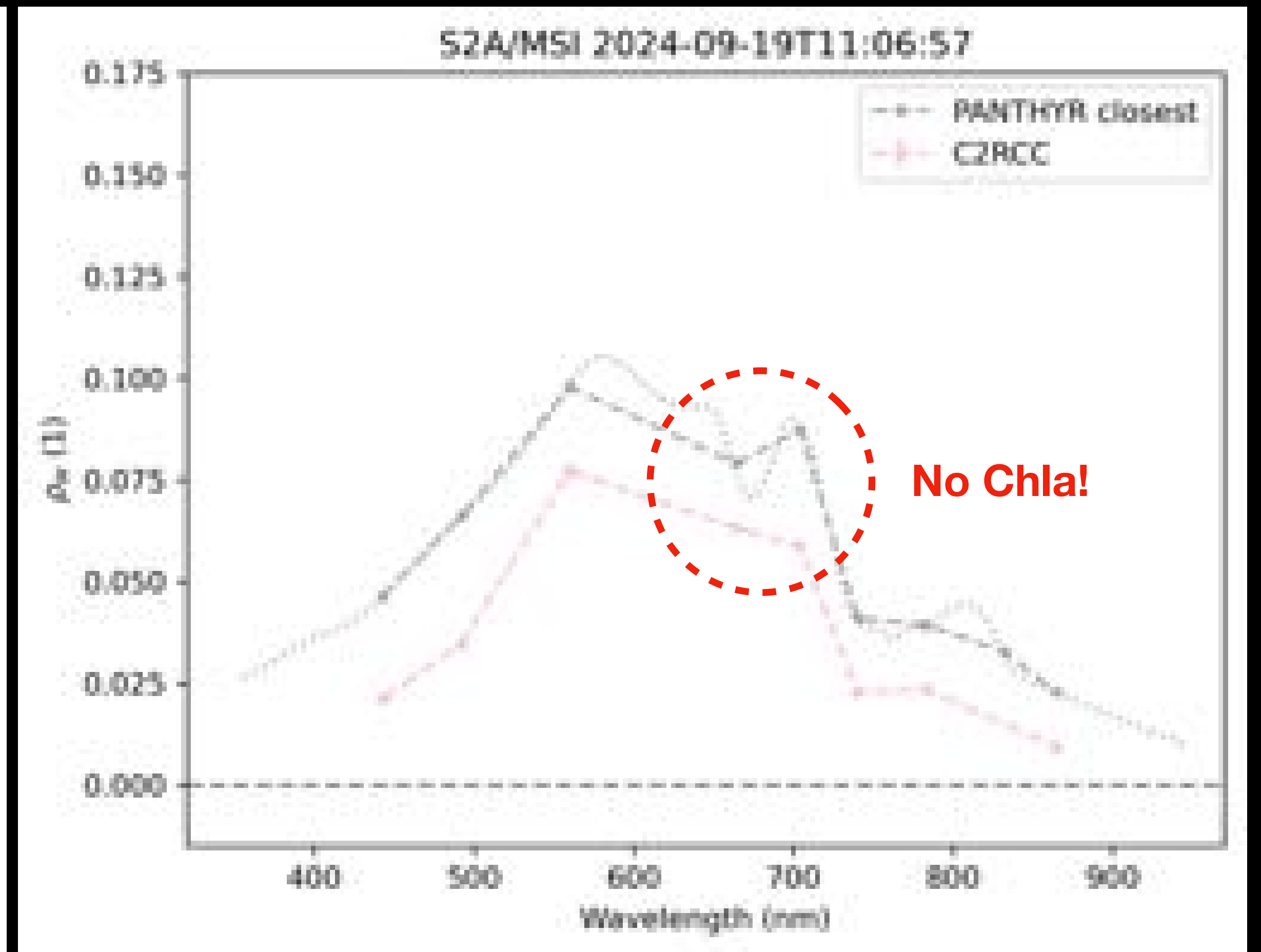


higher reflectance than I2gen/POLYMER, but red absorption feature has disappeared

C2RCC

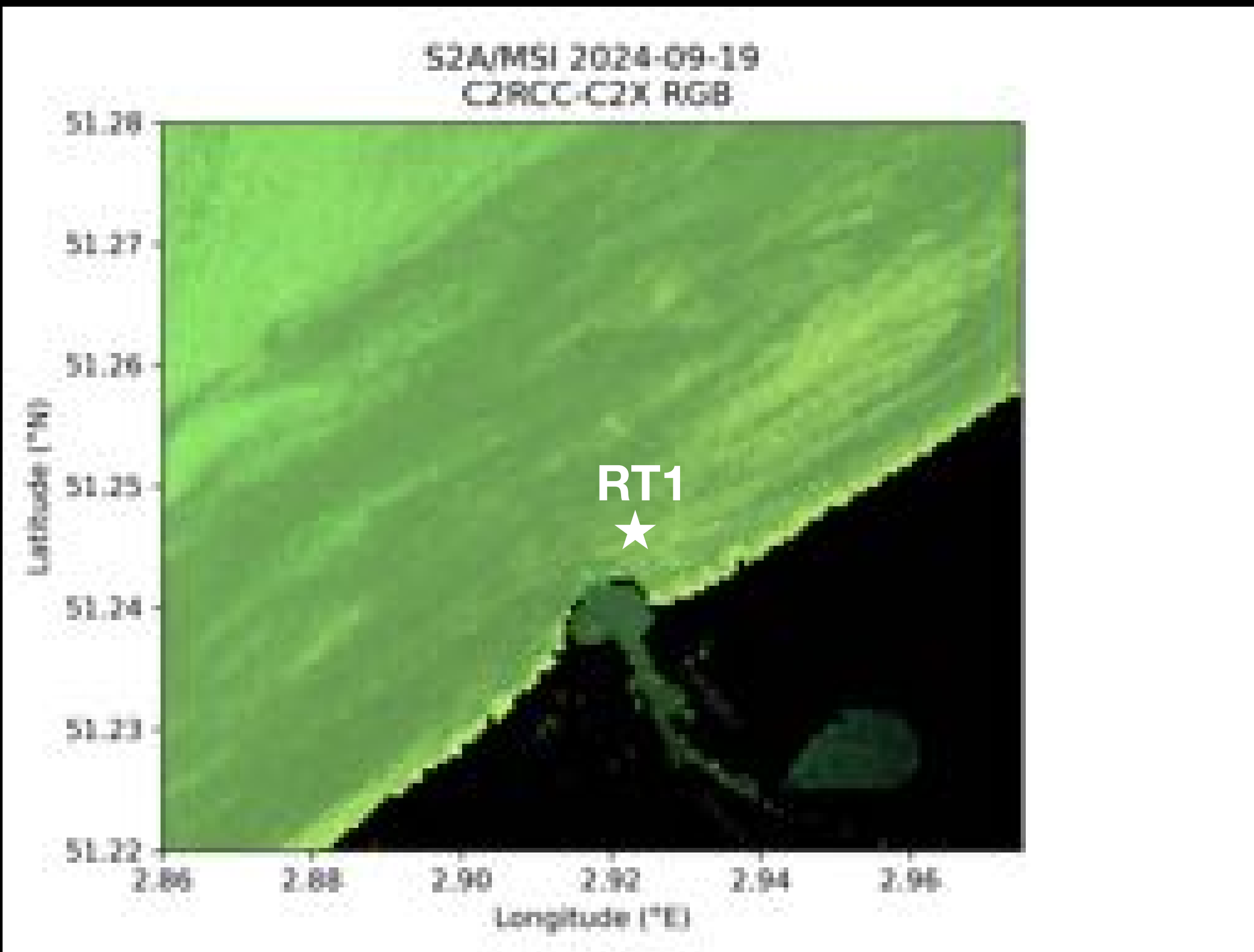


a bit brighter than I2gen/POLYMER, brown over most turbid areas

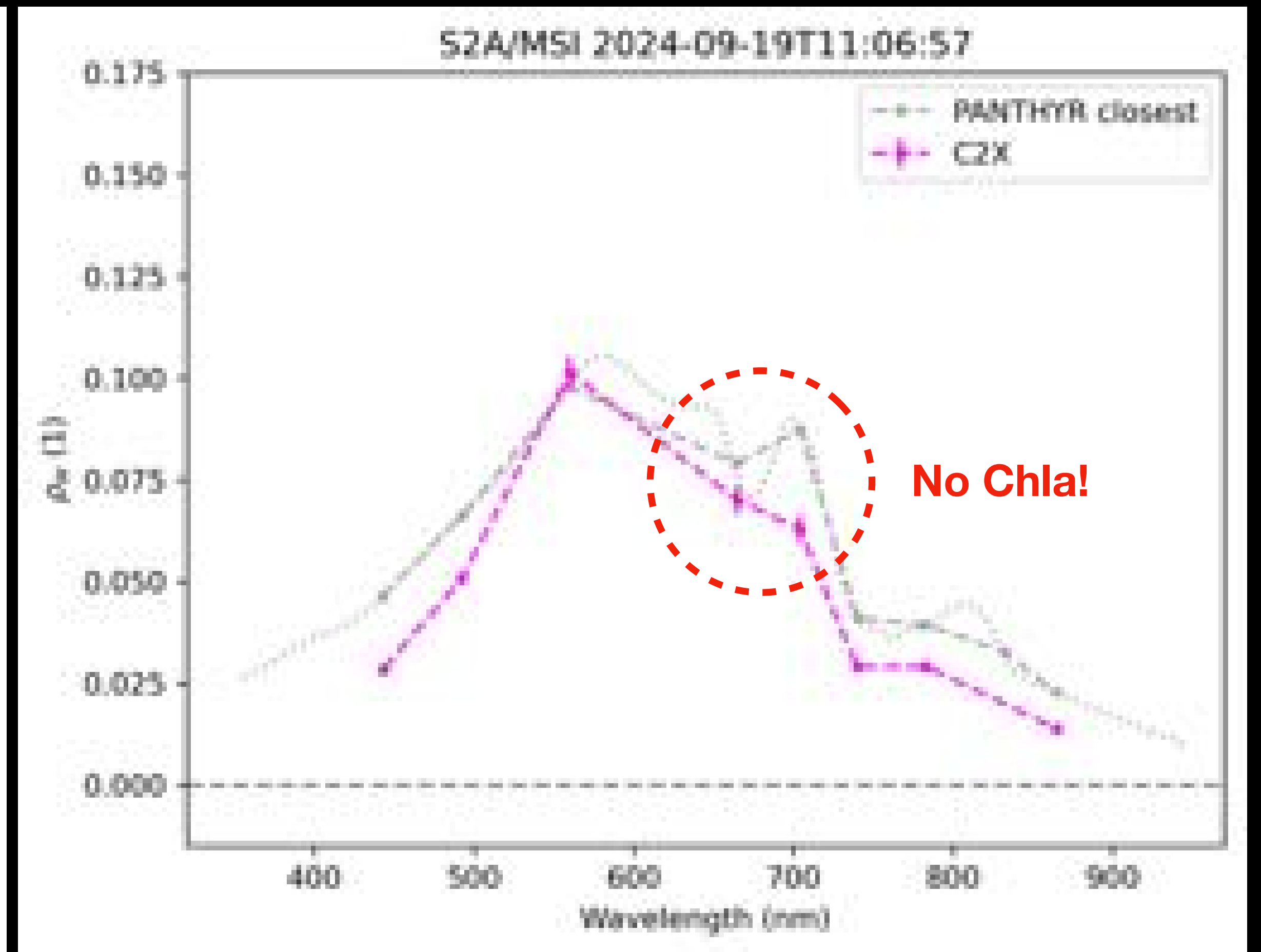


higher reflectance than I2gen/POLYMER, but red absorption feature has disappeared

C2RCC-C2X

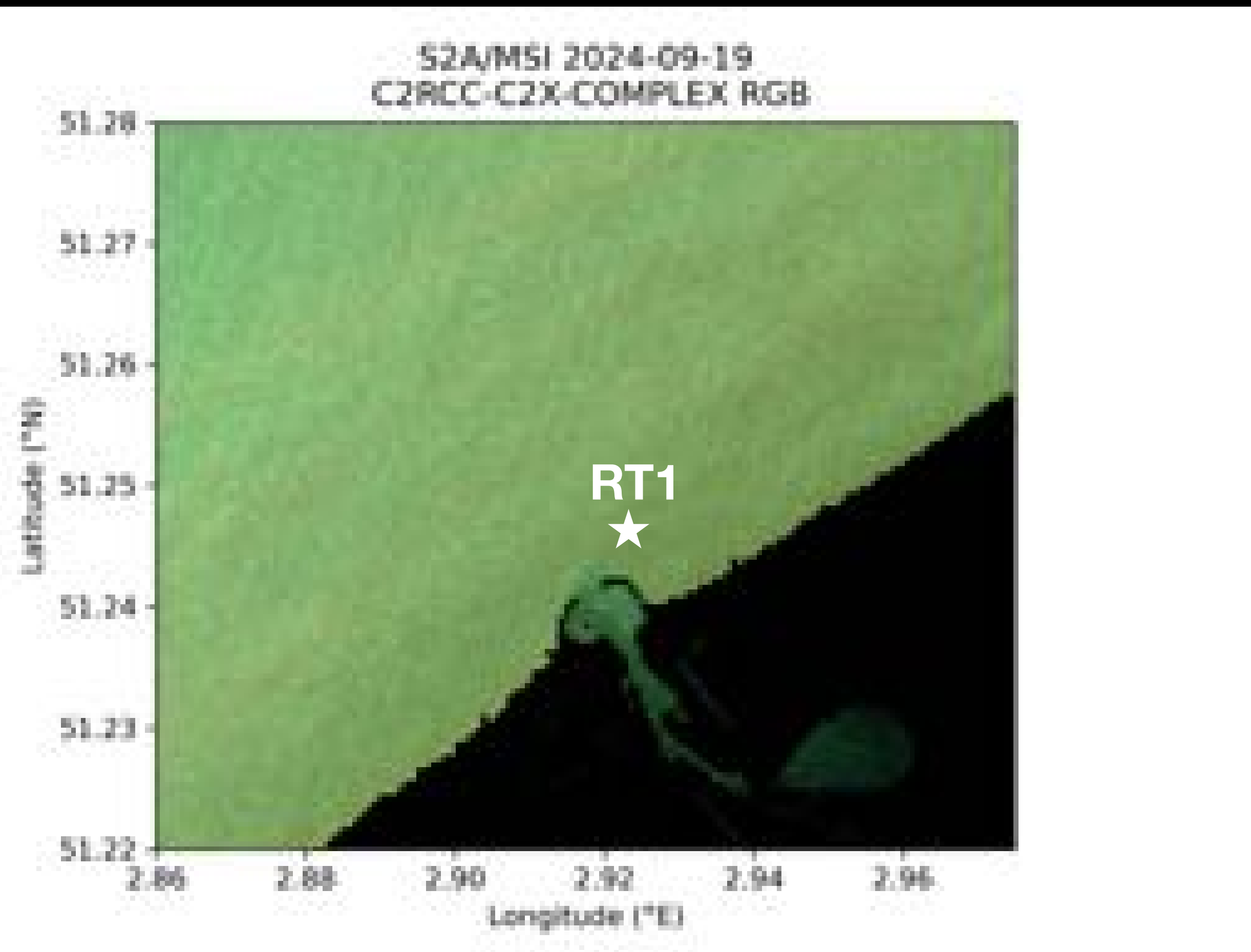


a bit brighter than C2RCC, more patchy, more noise

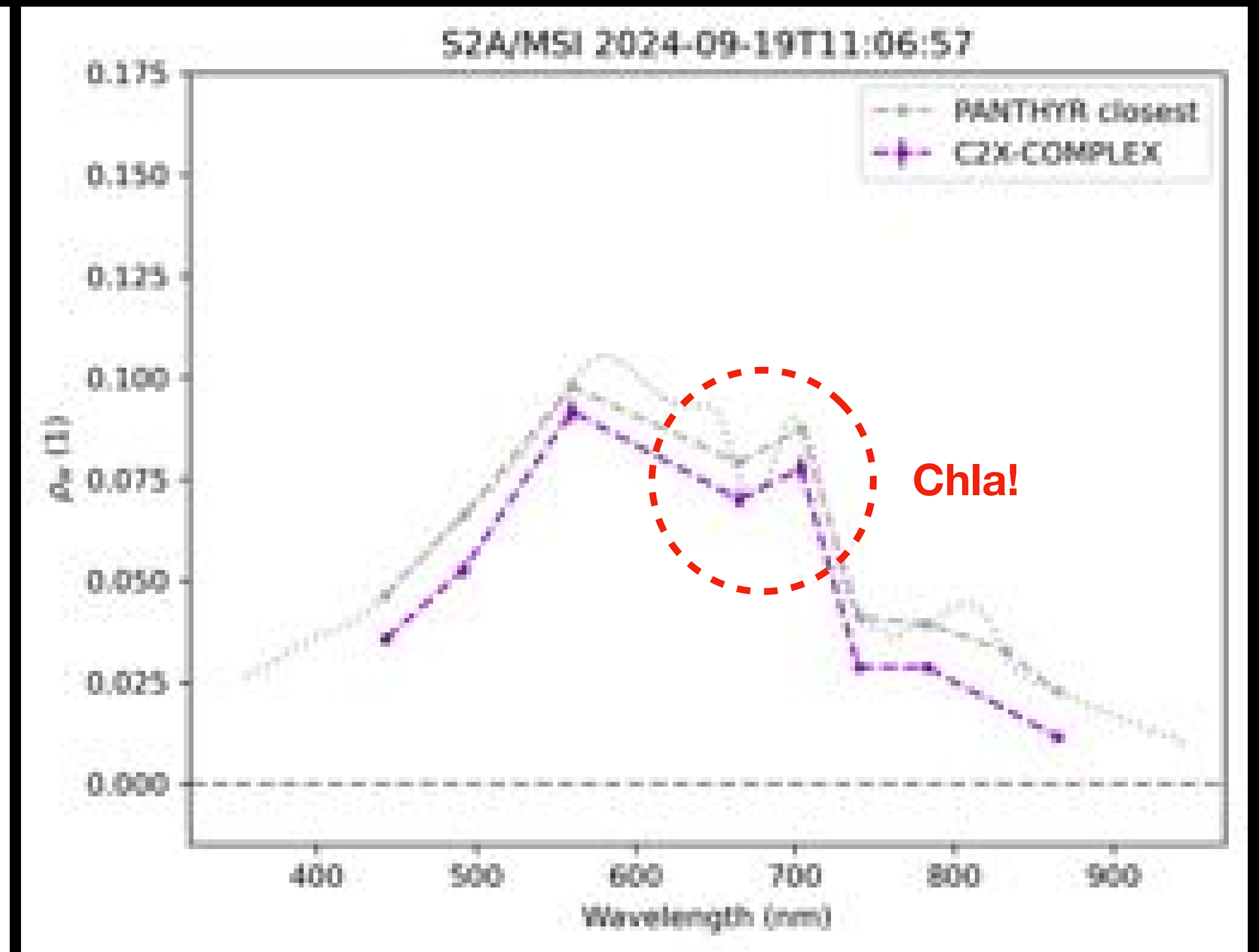


better fit compared to C2RCC, but red absorption feature missing

C2RCC-COMPLEX

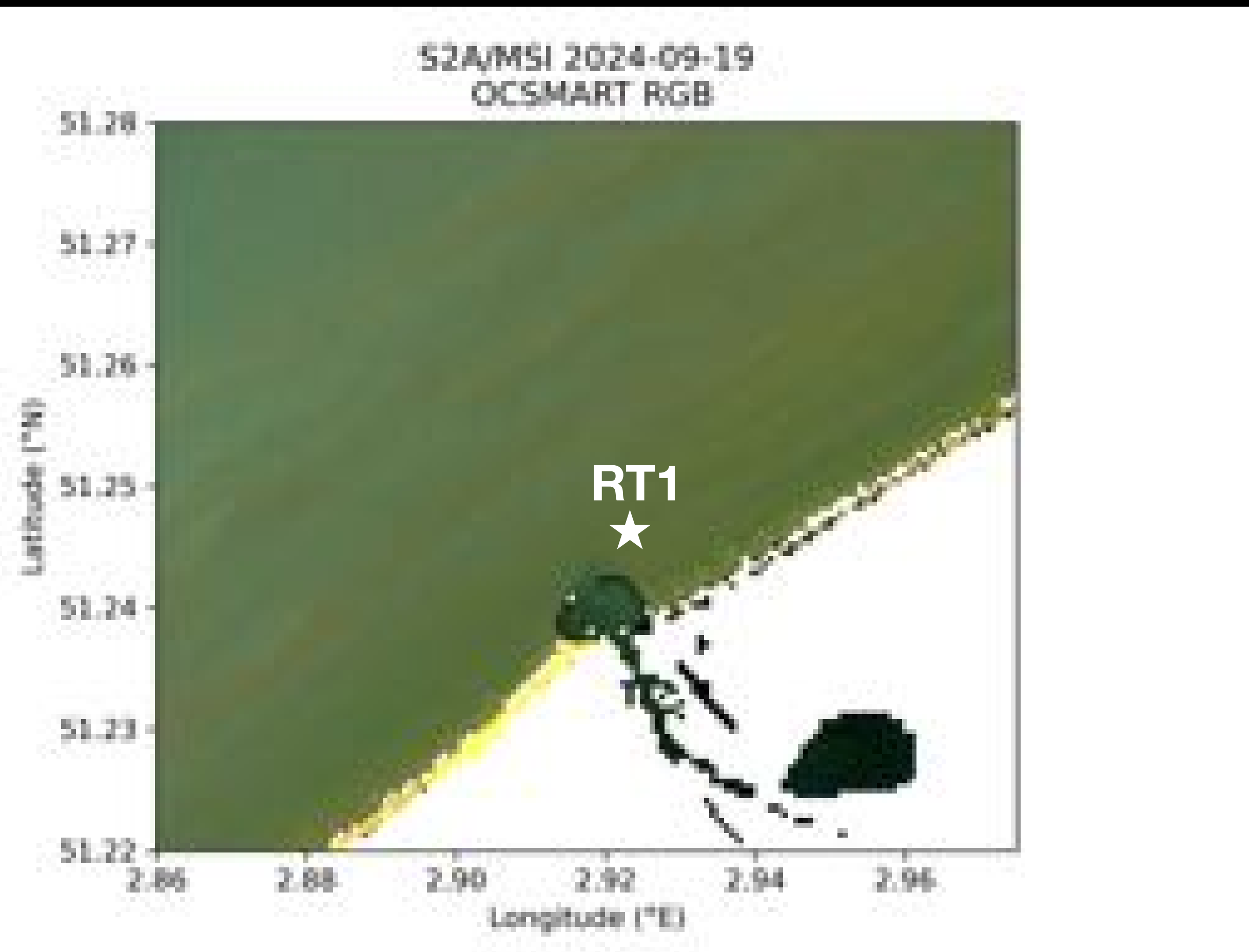


a bit brighter than C2RCC, more noise, spatial variability reduced

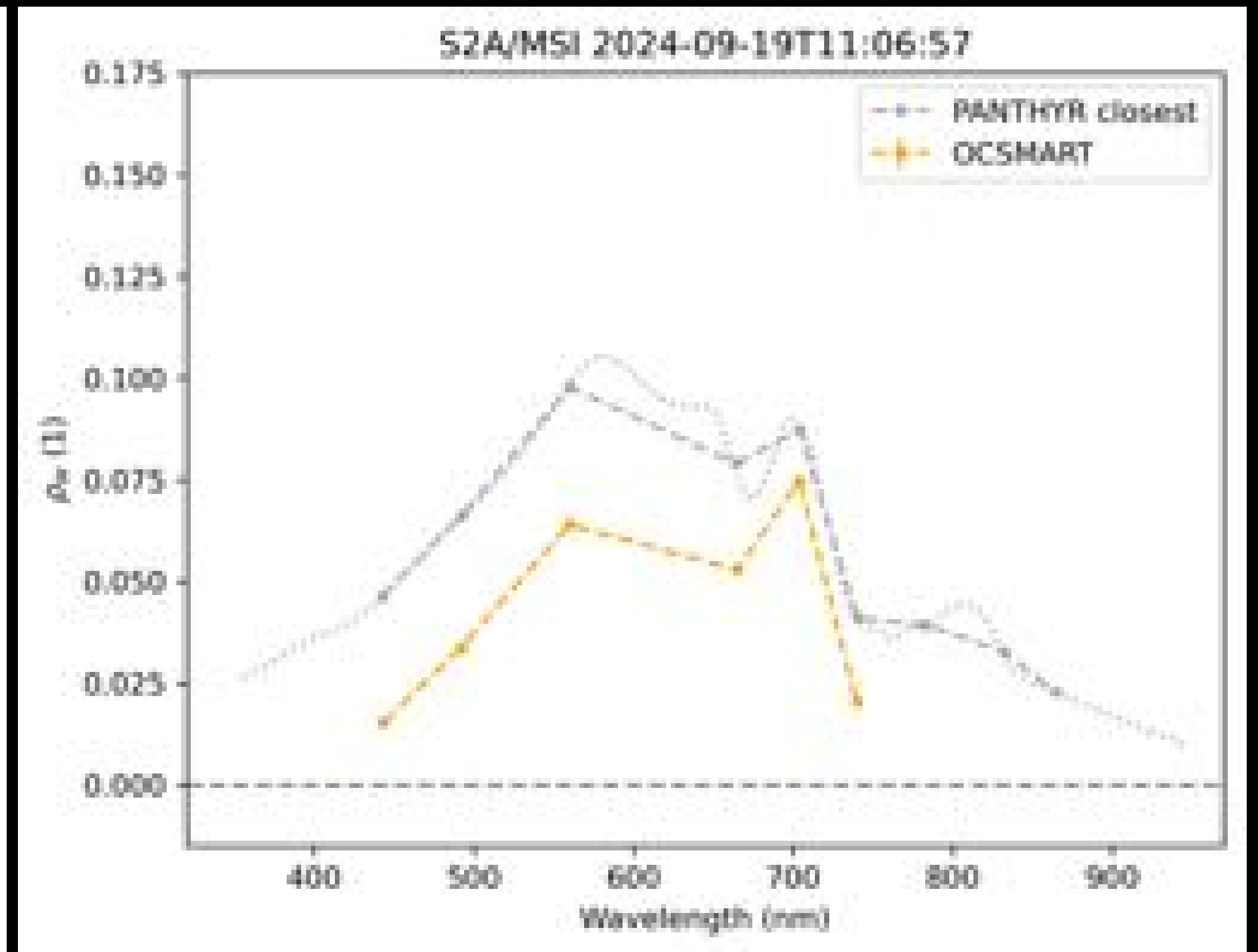


better fit compared to C2RCC and C2X, red absorption feature reappears

OC-SMART

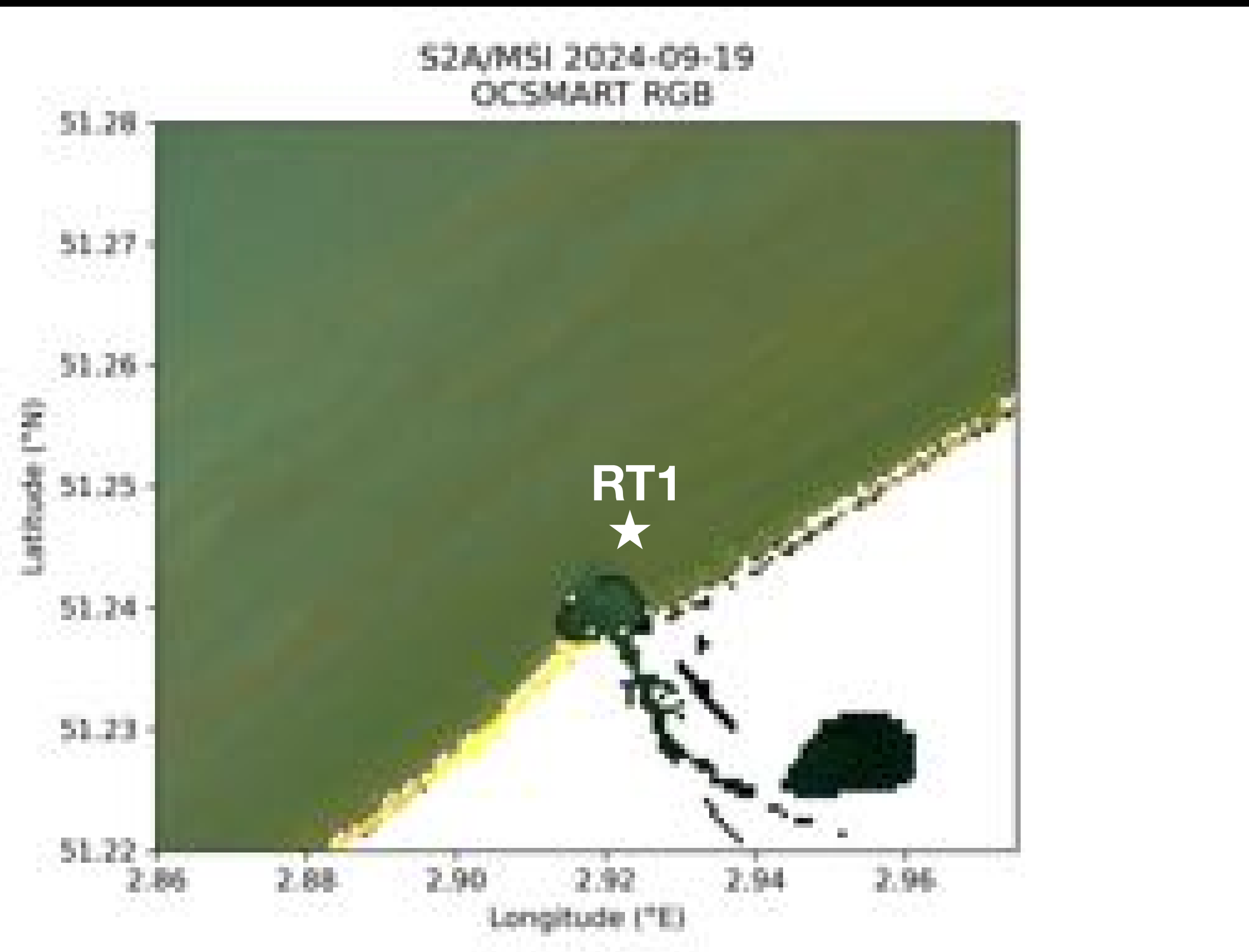


lower reflectance, comparable to POLYMER, less difference over most turbid waters

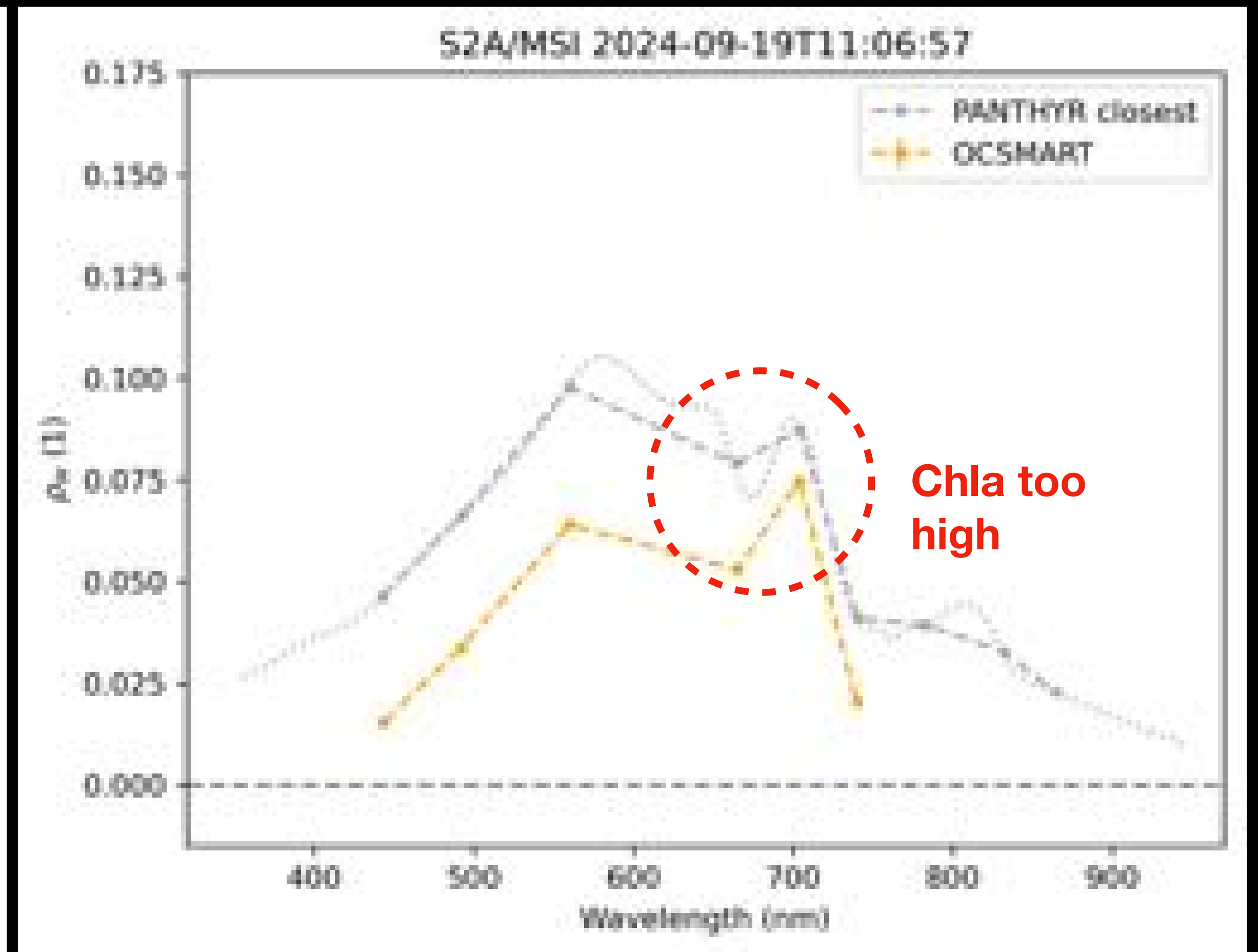


overcorrection in VIS , red absorption feature exaggerated

OC-SMART

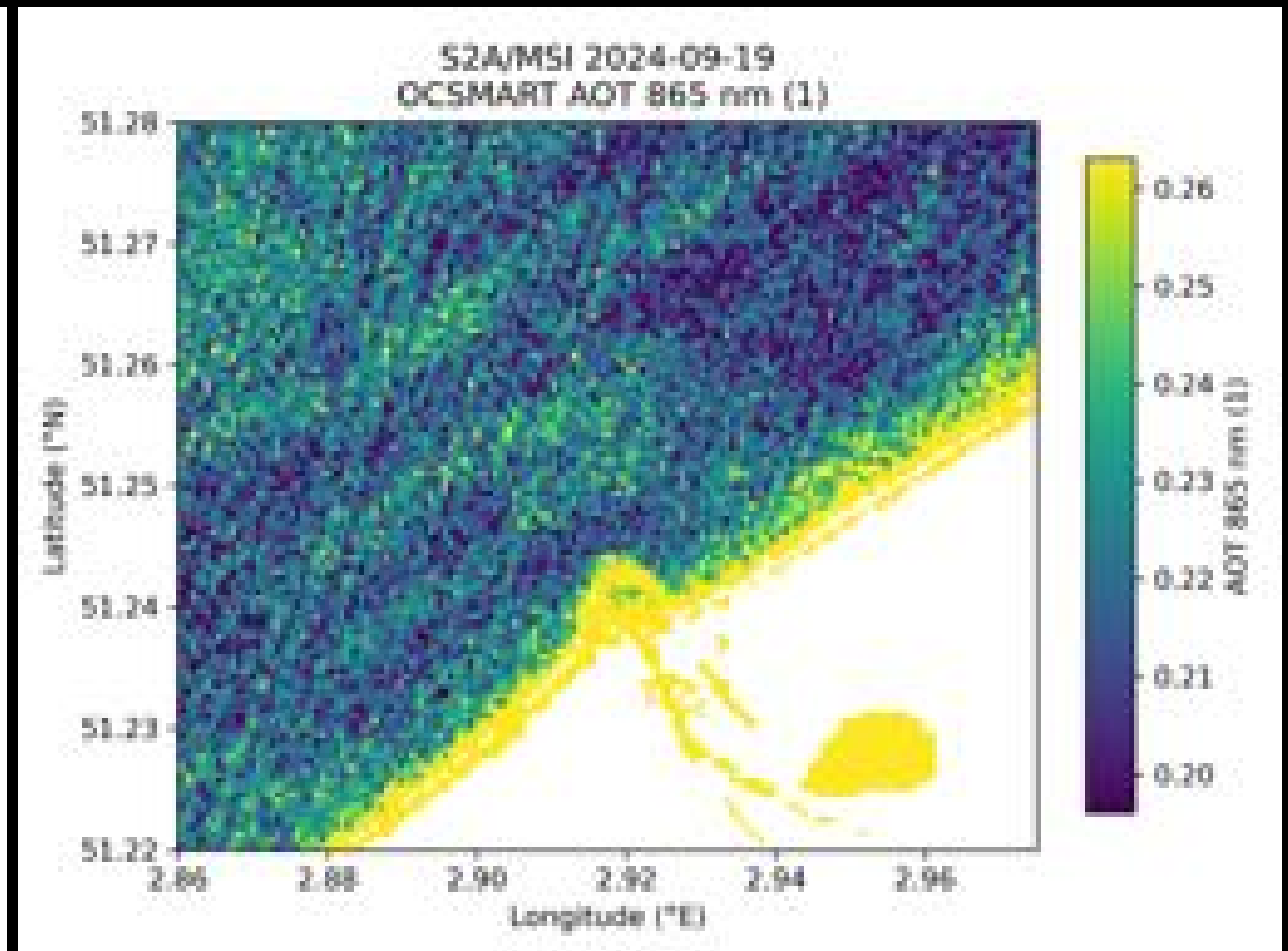
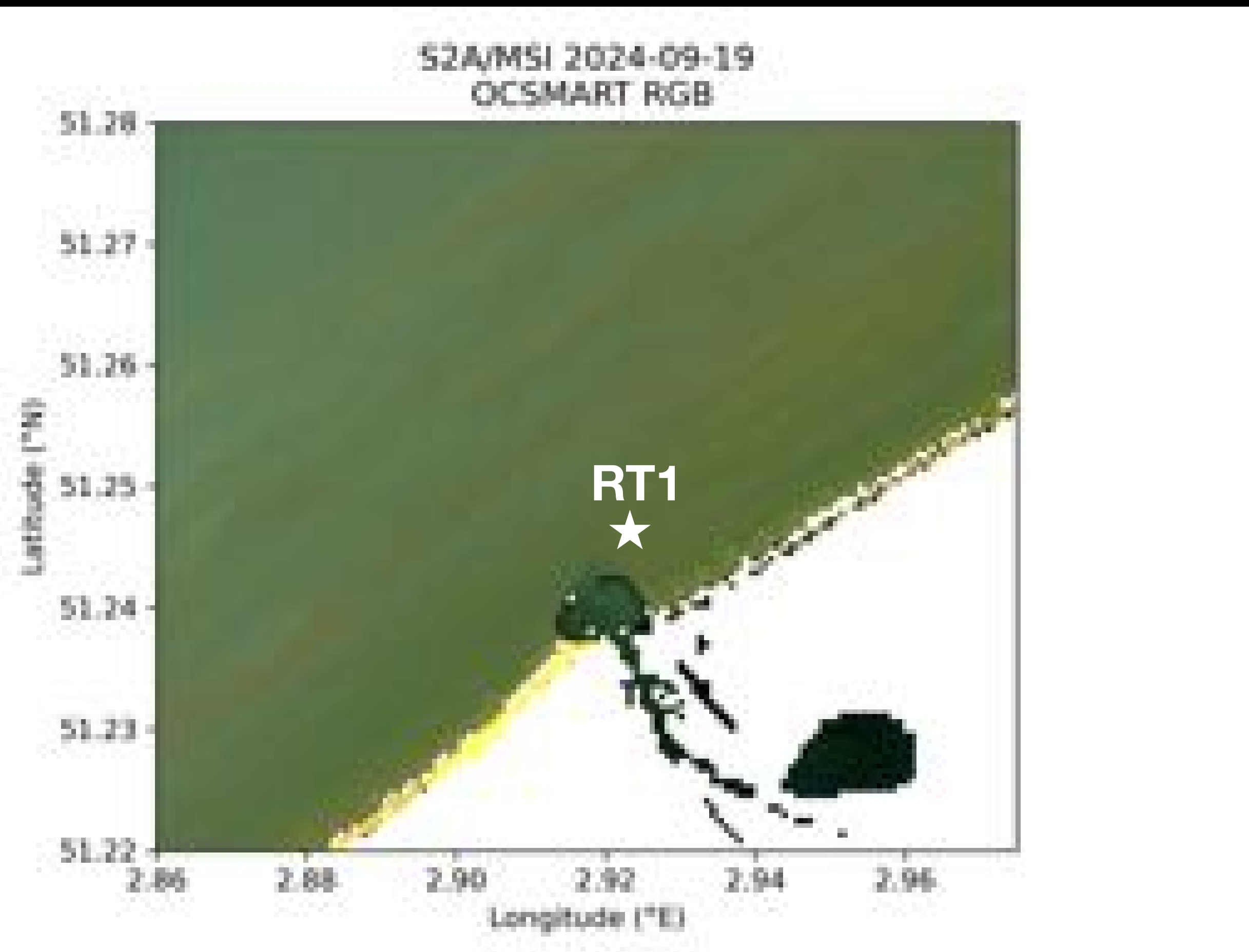


lower reflectance, comparable to POLYMER, less difference over most turbid waters



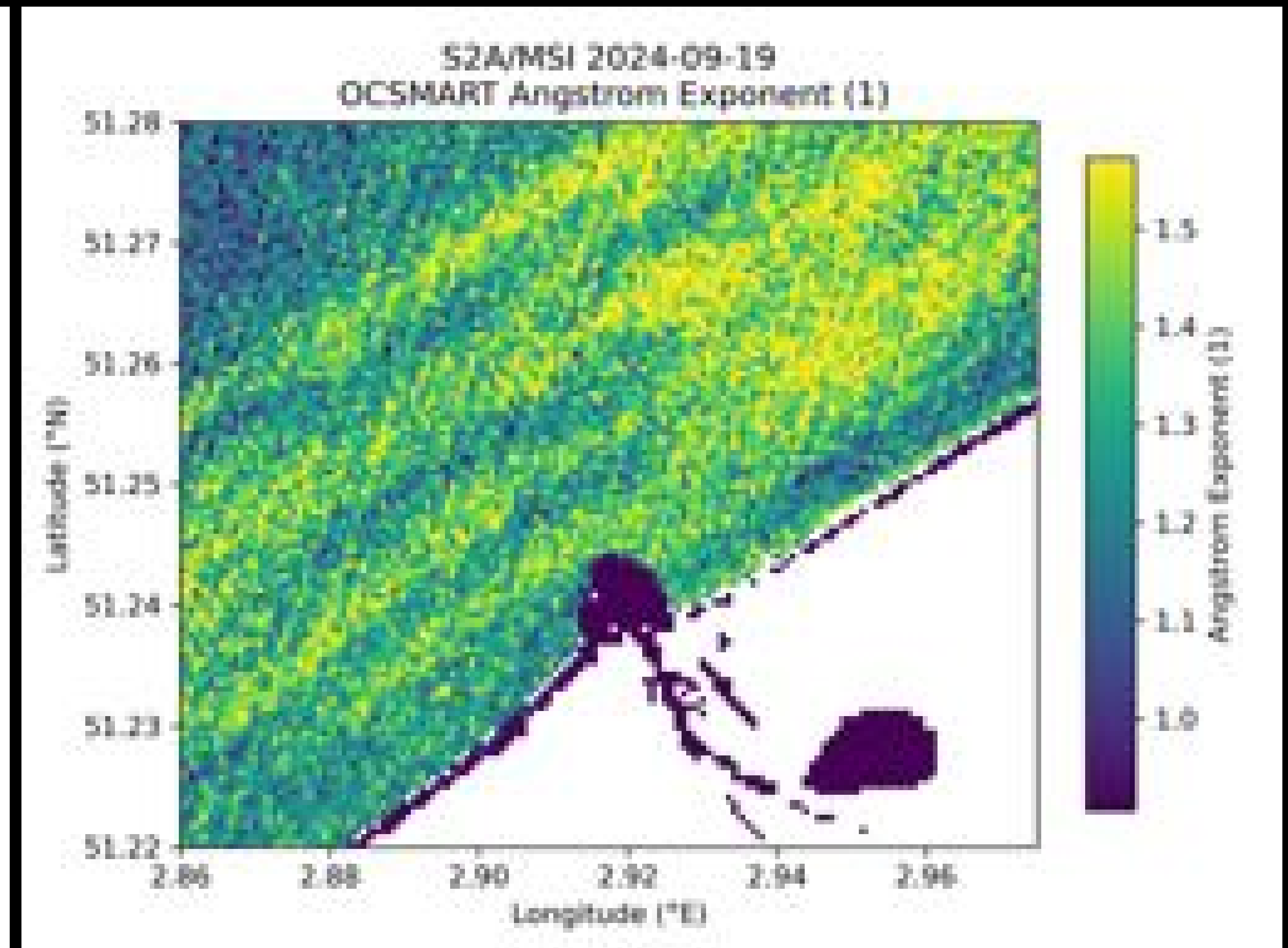
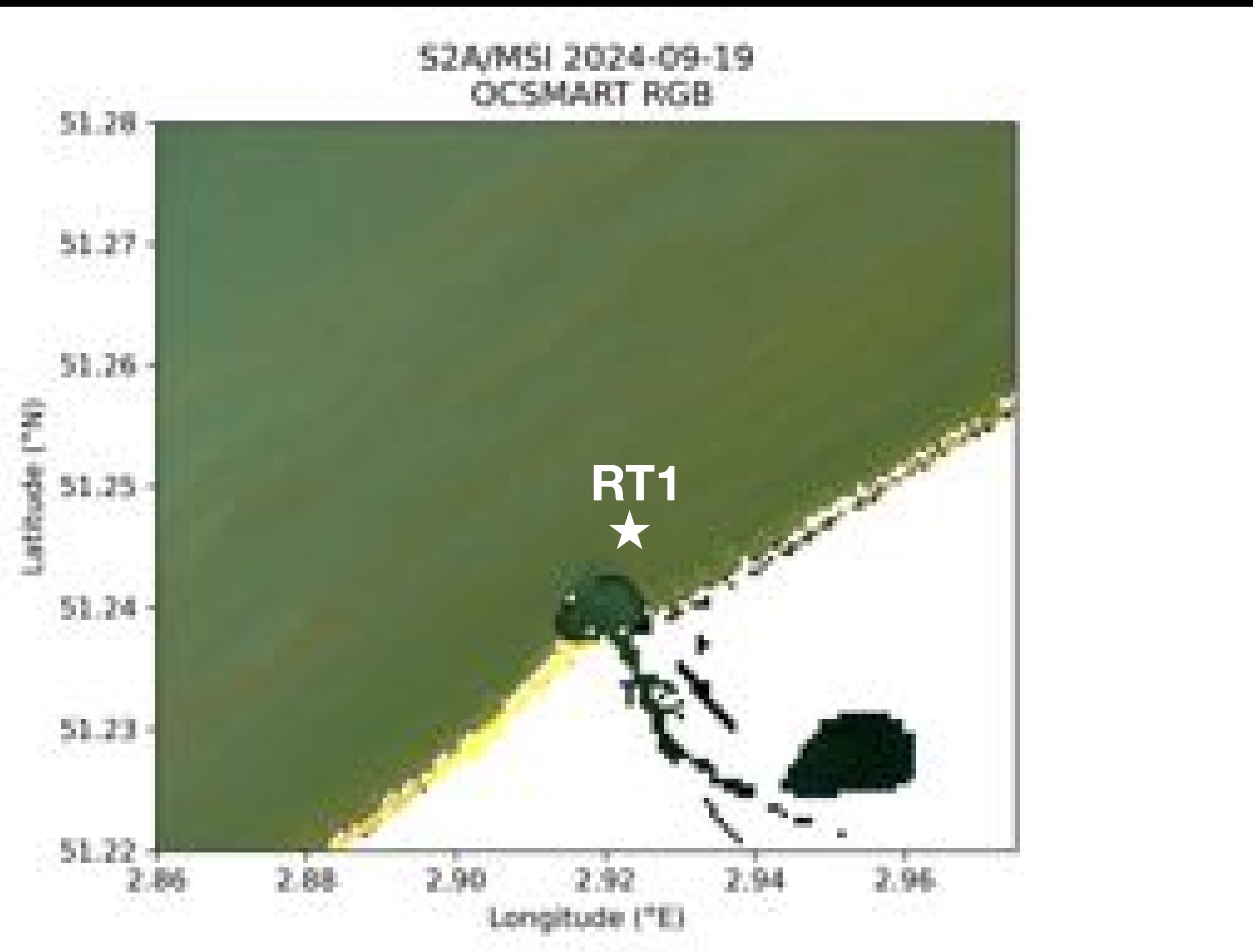
overcorrection in VIS , red absorption feature exaggerated

OC-SMART



aerosol optical depth ~ some water patterns, noisy,
high in the port and lake

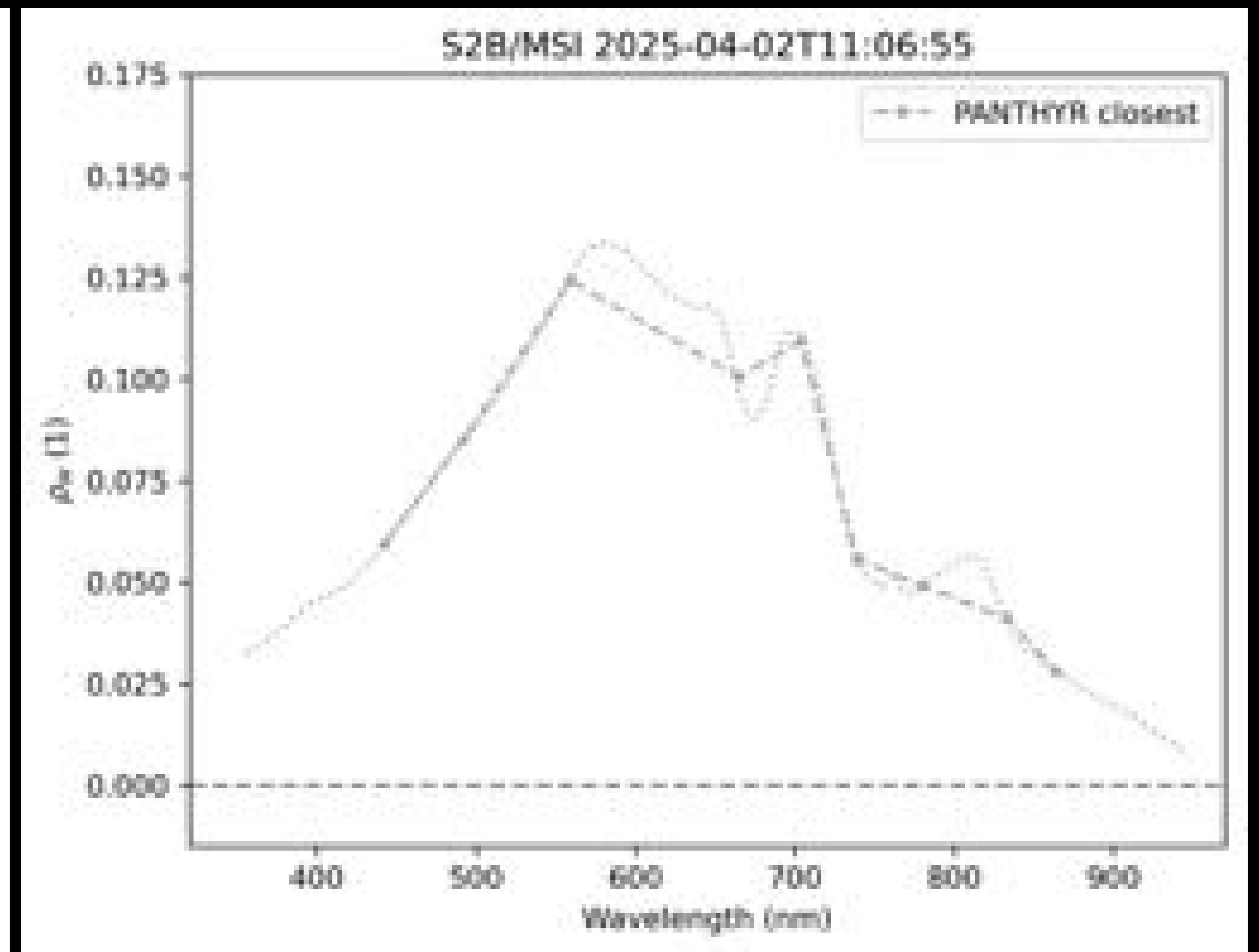
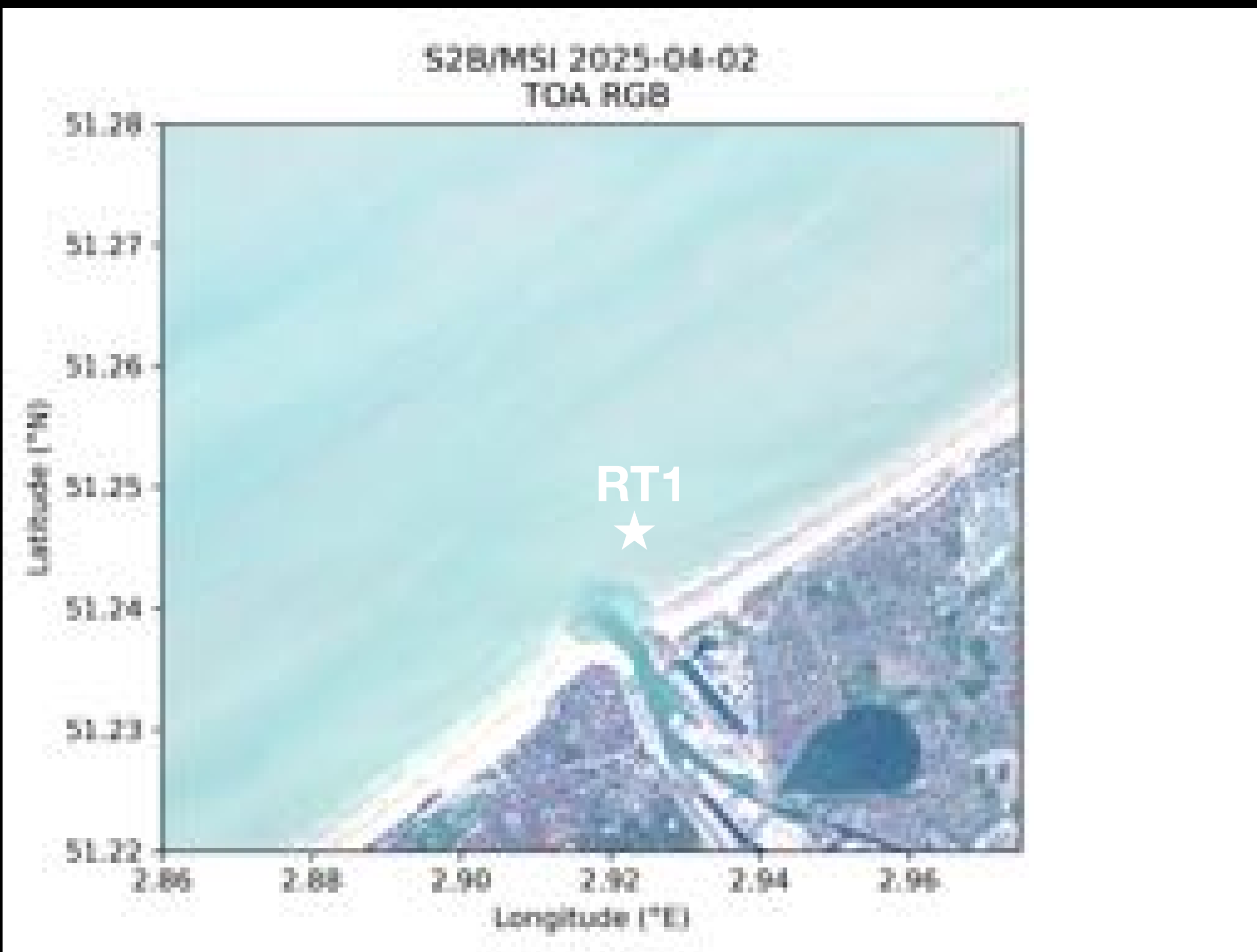
OC-SMART



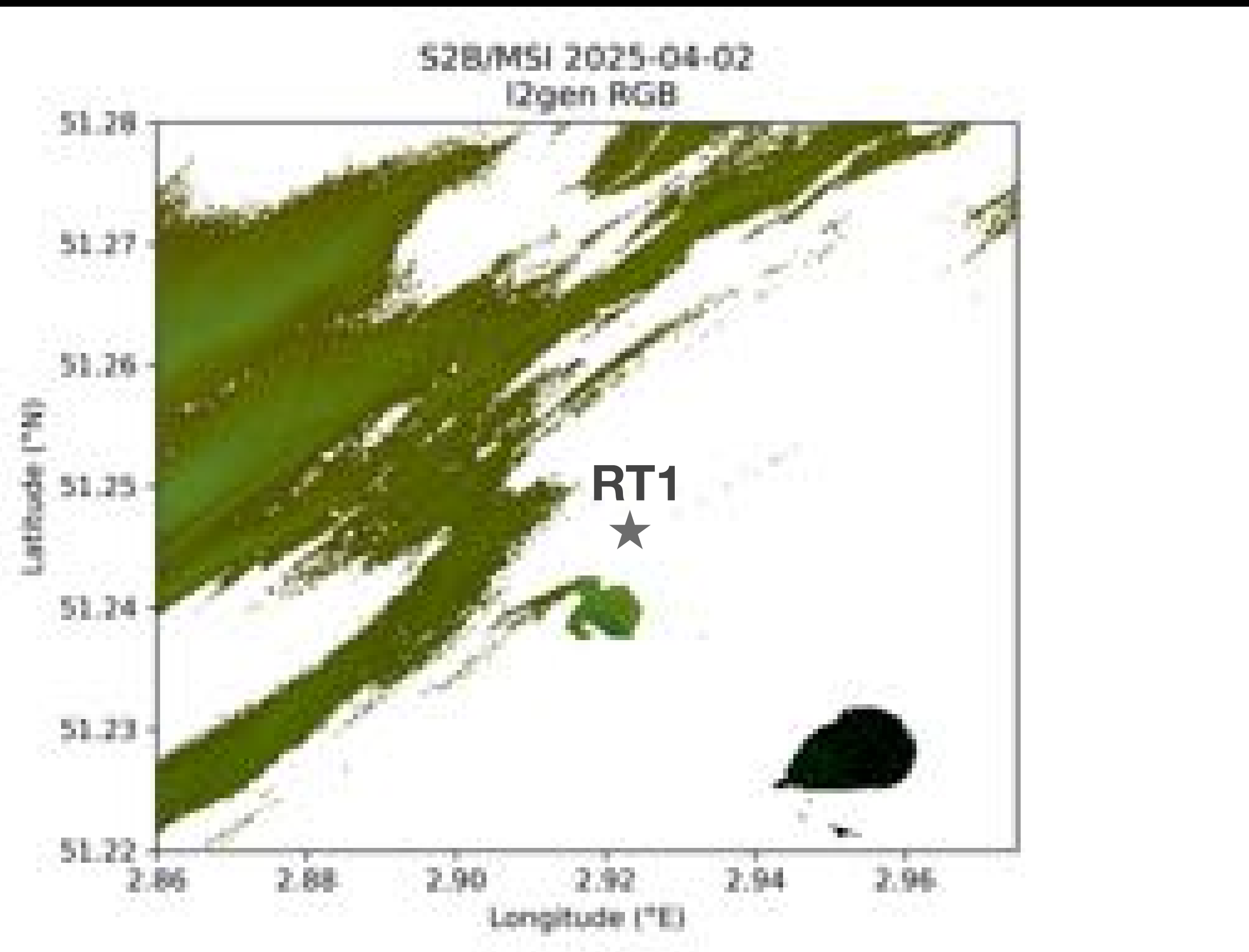
Angstrom ~ some water patterns, very low in port and lake

TOA 2025-04-02

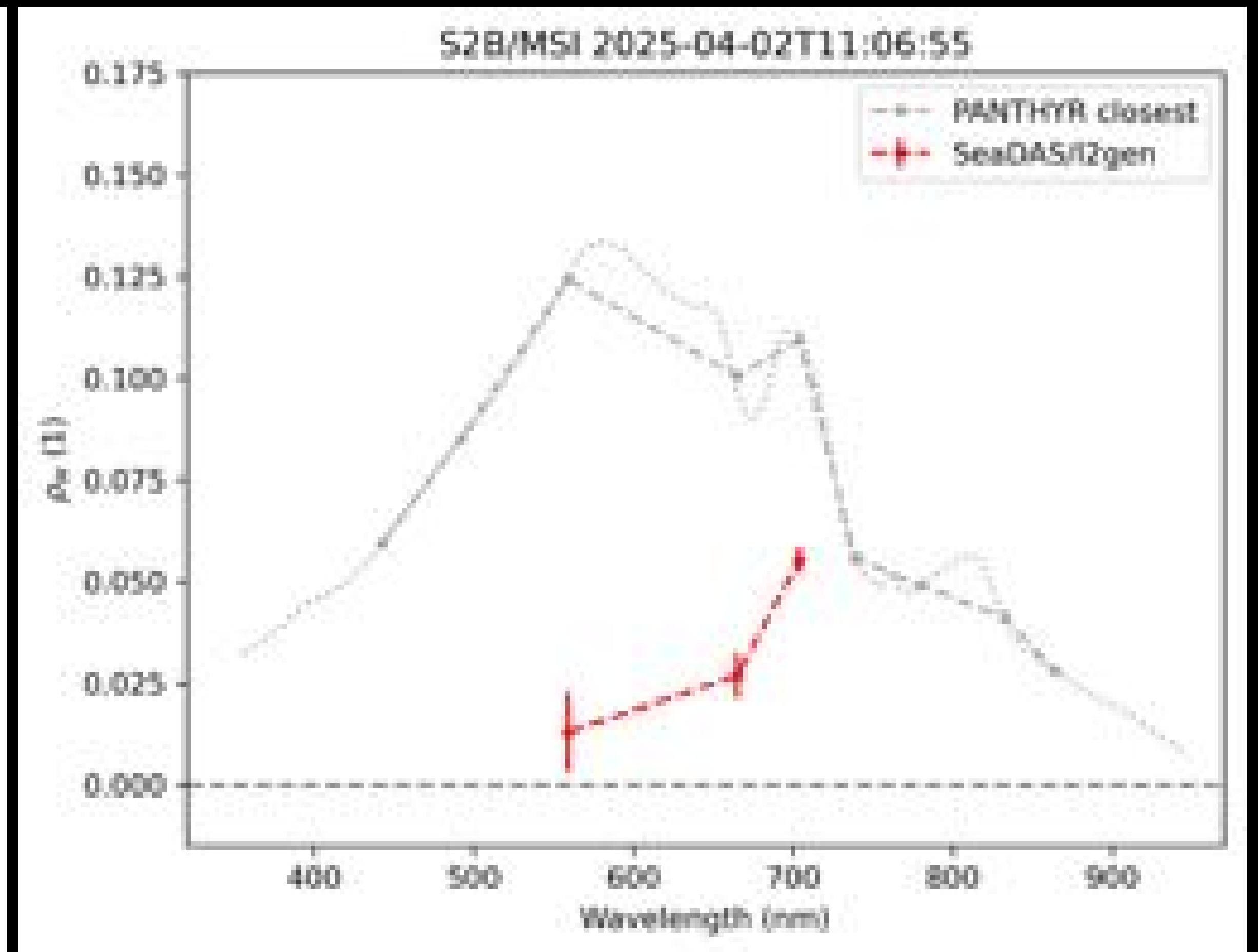
PANTHYR



I2gen

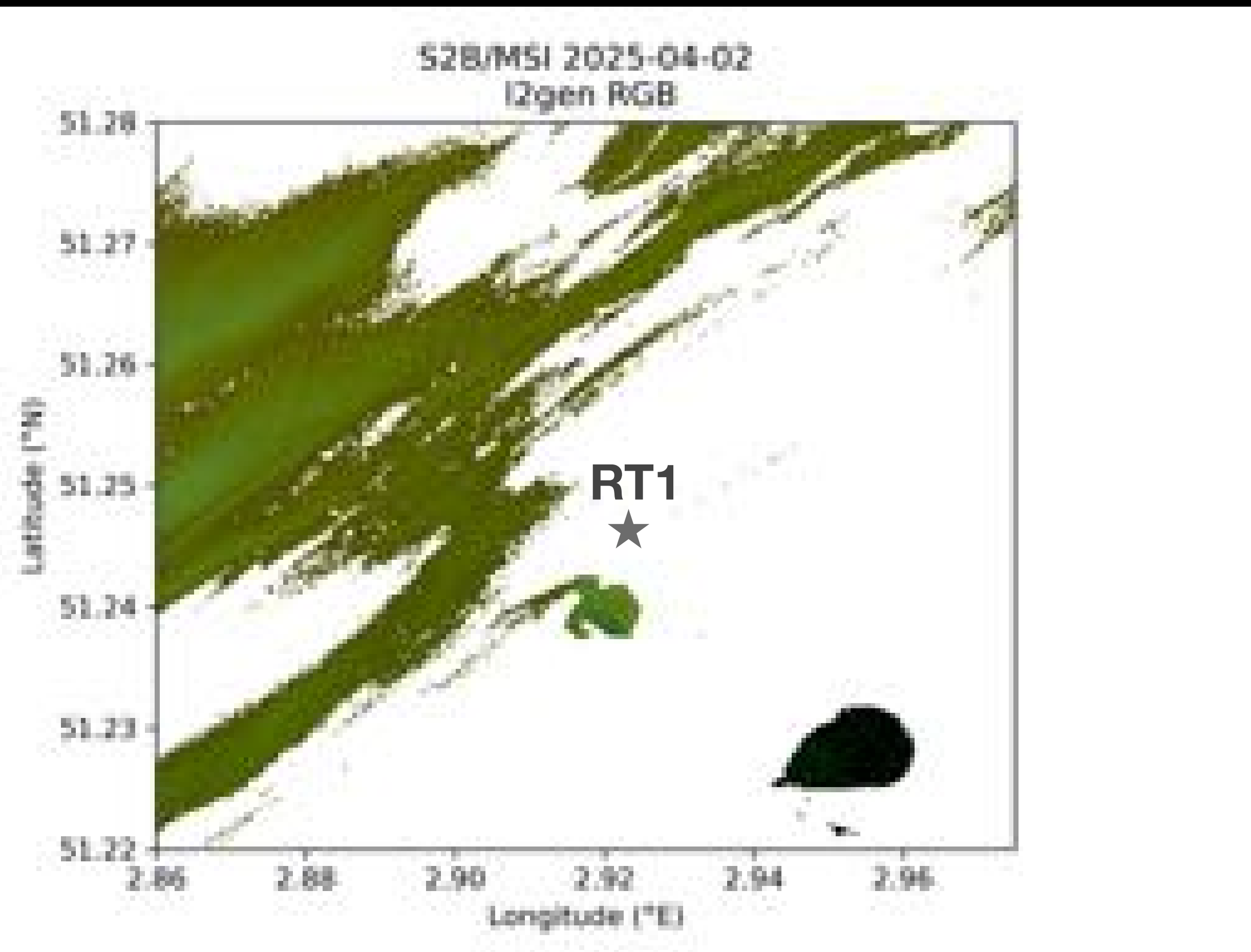


green/brown appearance, many pixels masked (Blue band << 0)

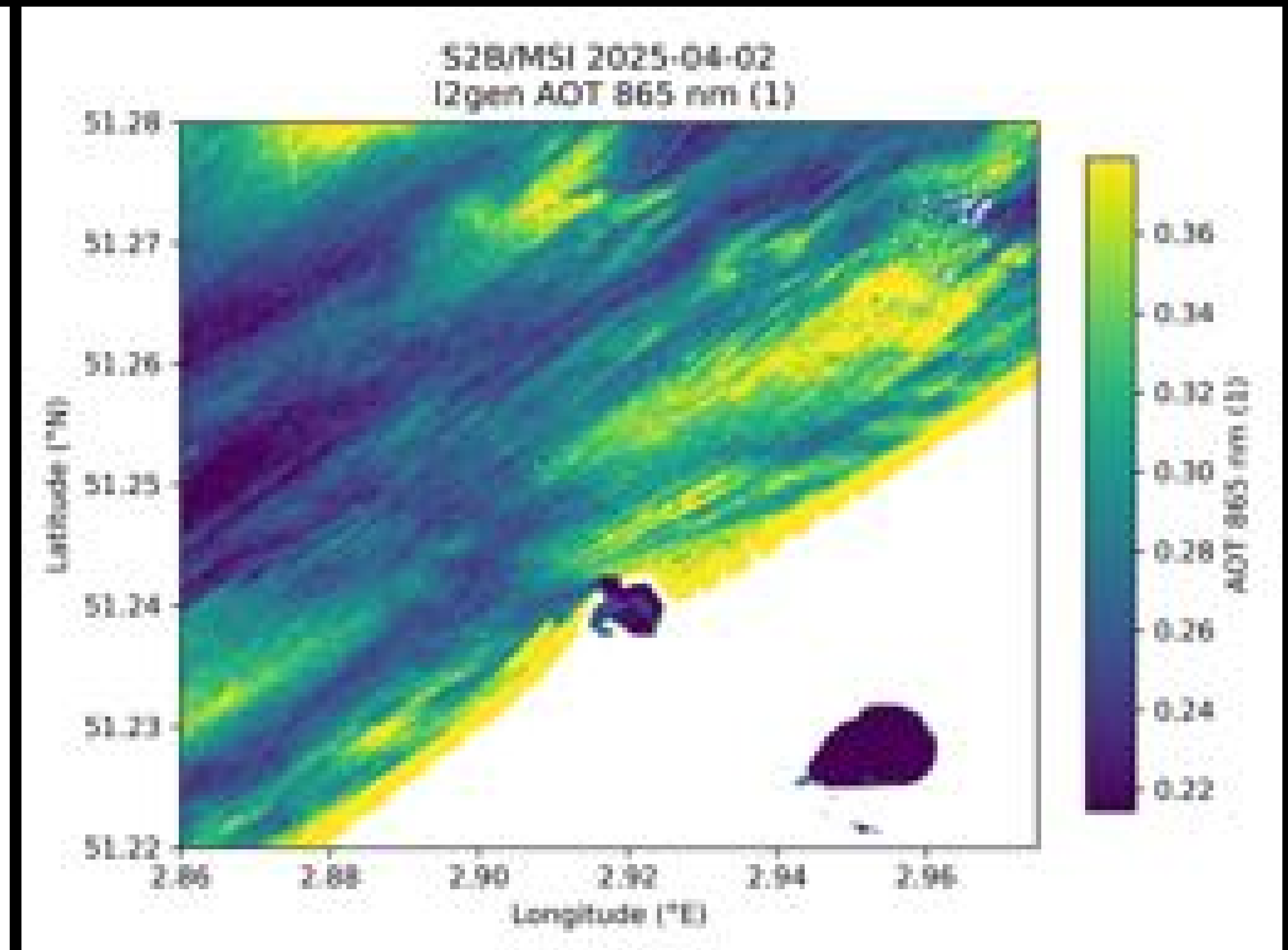


significant overcorrection

I2gen

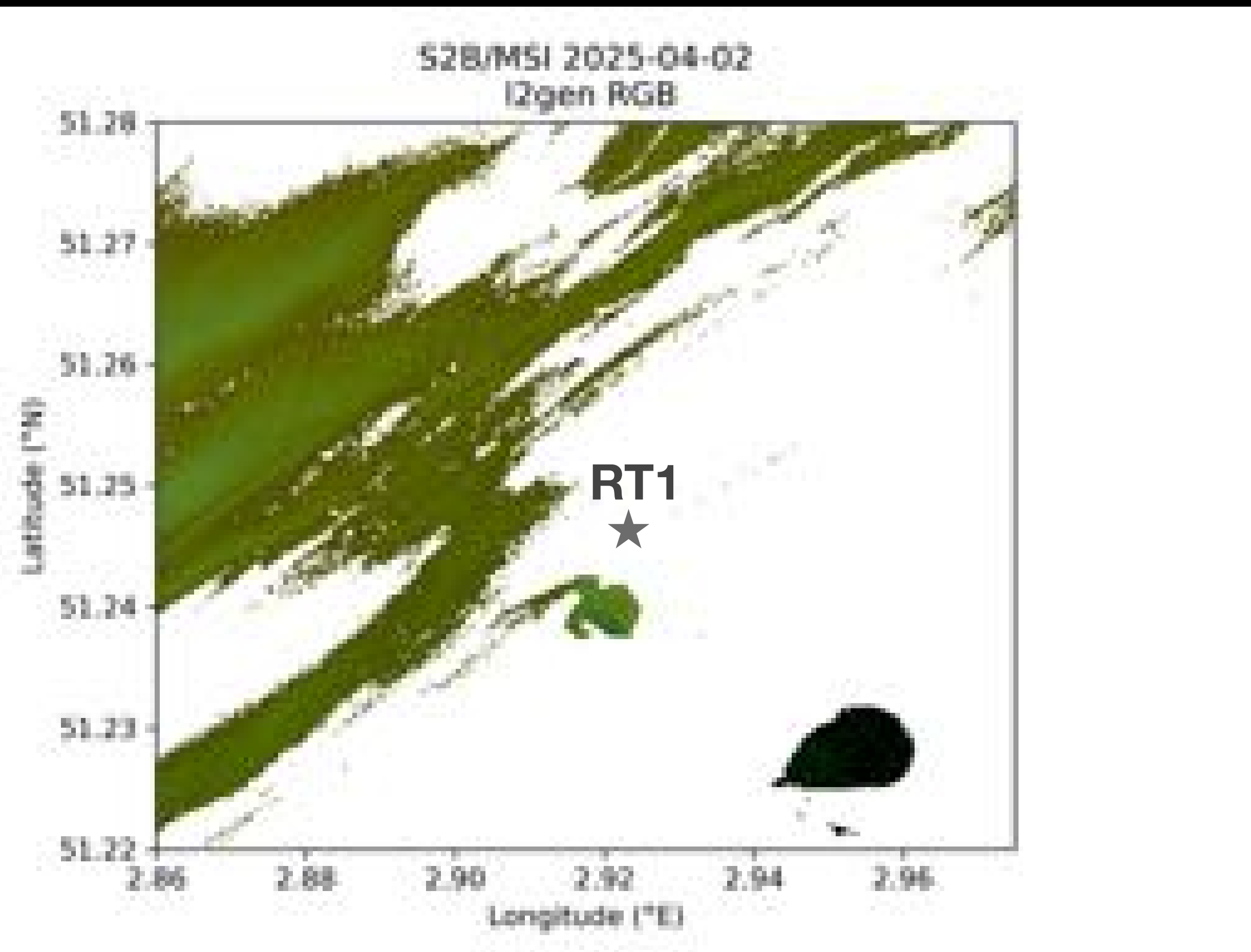


masking (blue band $\ll 0$) ~ high aerosol optical depth

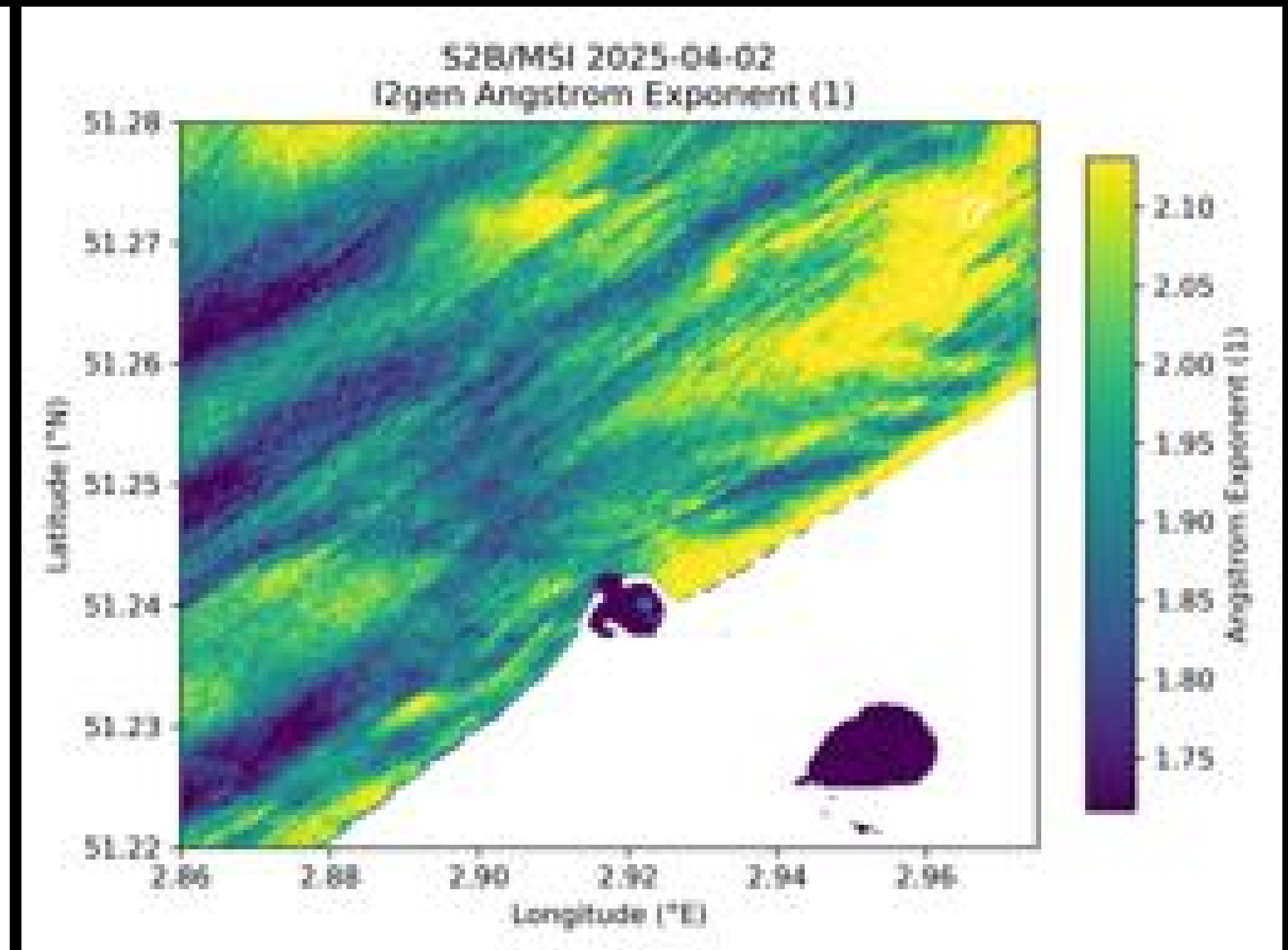


aerosol optical depth ~ water turbidity

I2gen

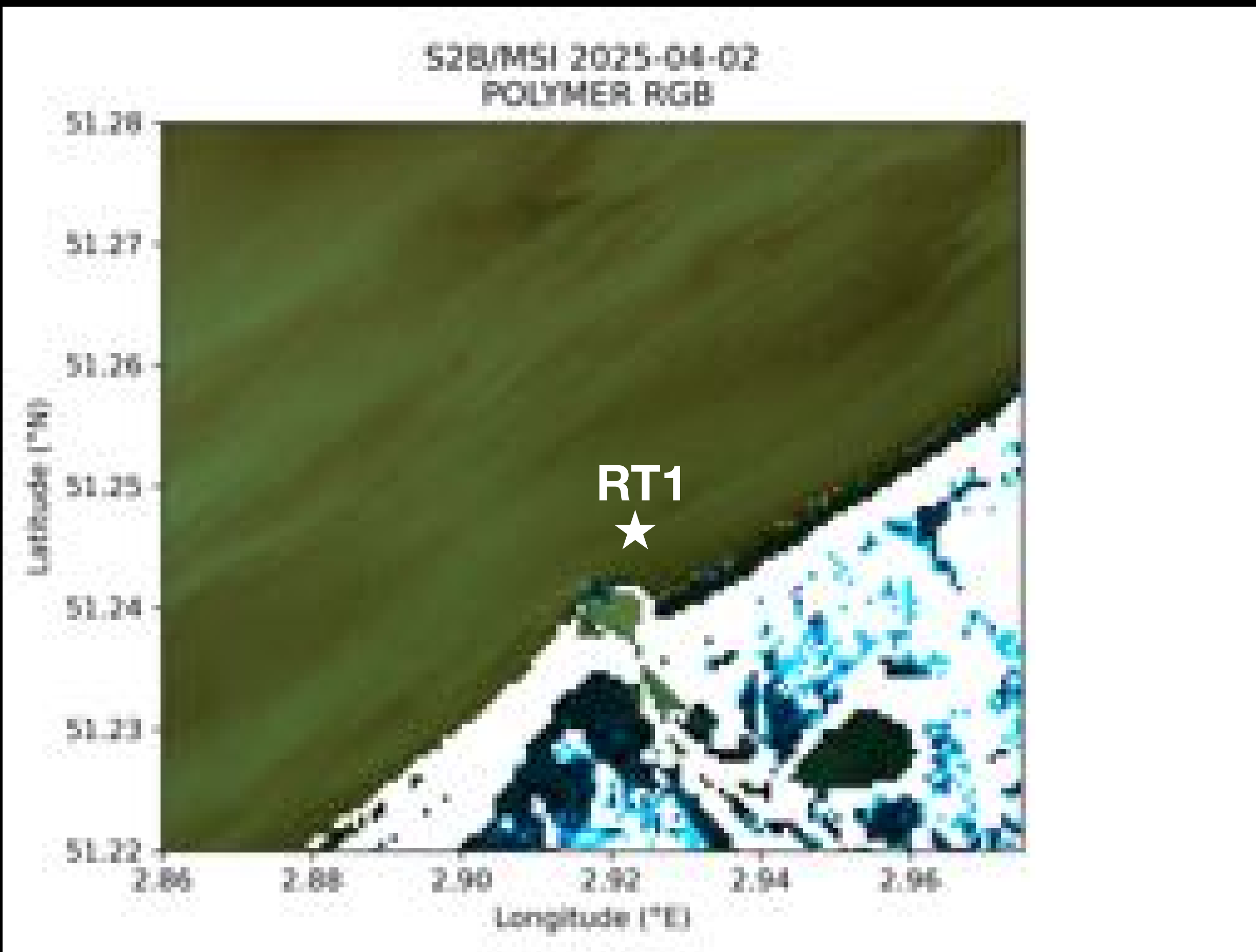


masking (blue band $\ll 0$) ~ high aerosol angstrom

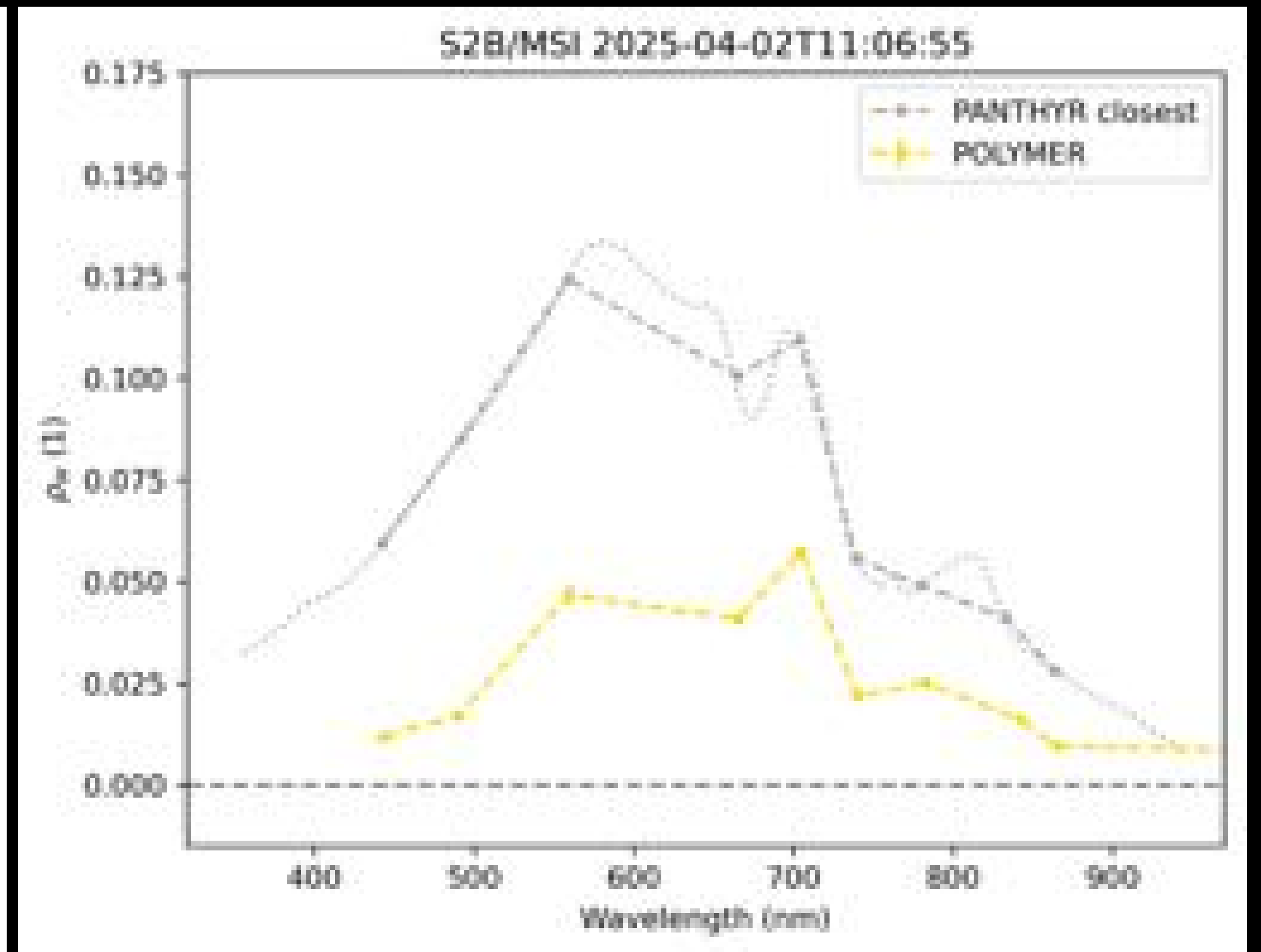


Angstrom ~ water turbidity

POLYMER

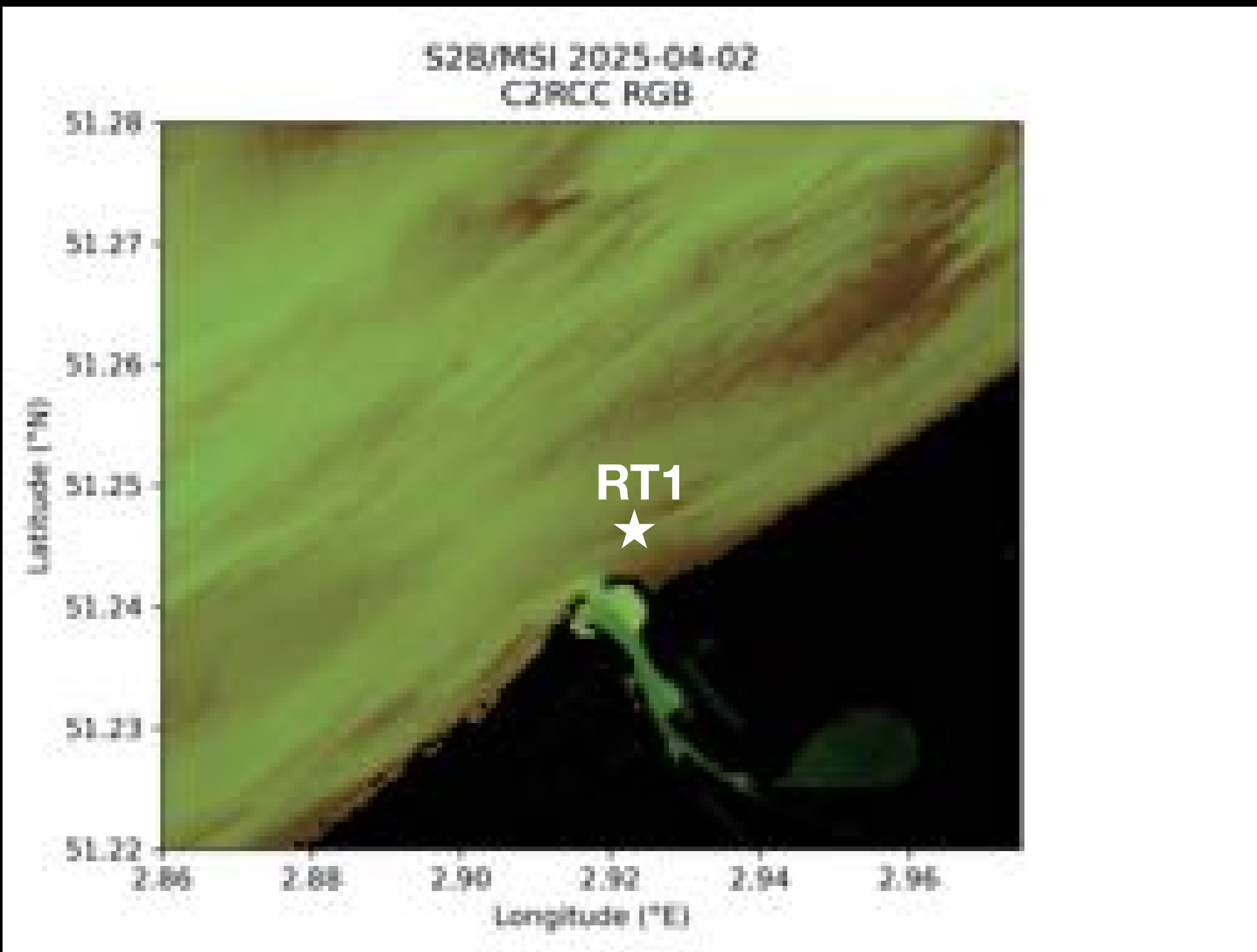


quite dark, mostly green and brown areas

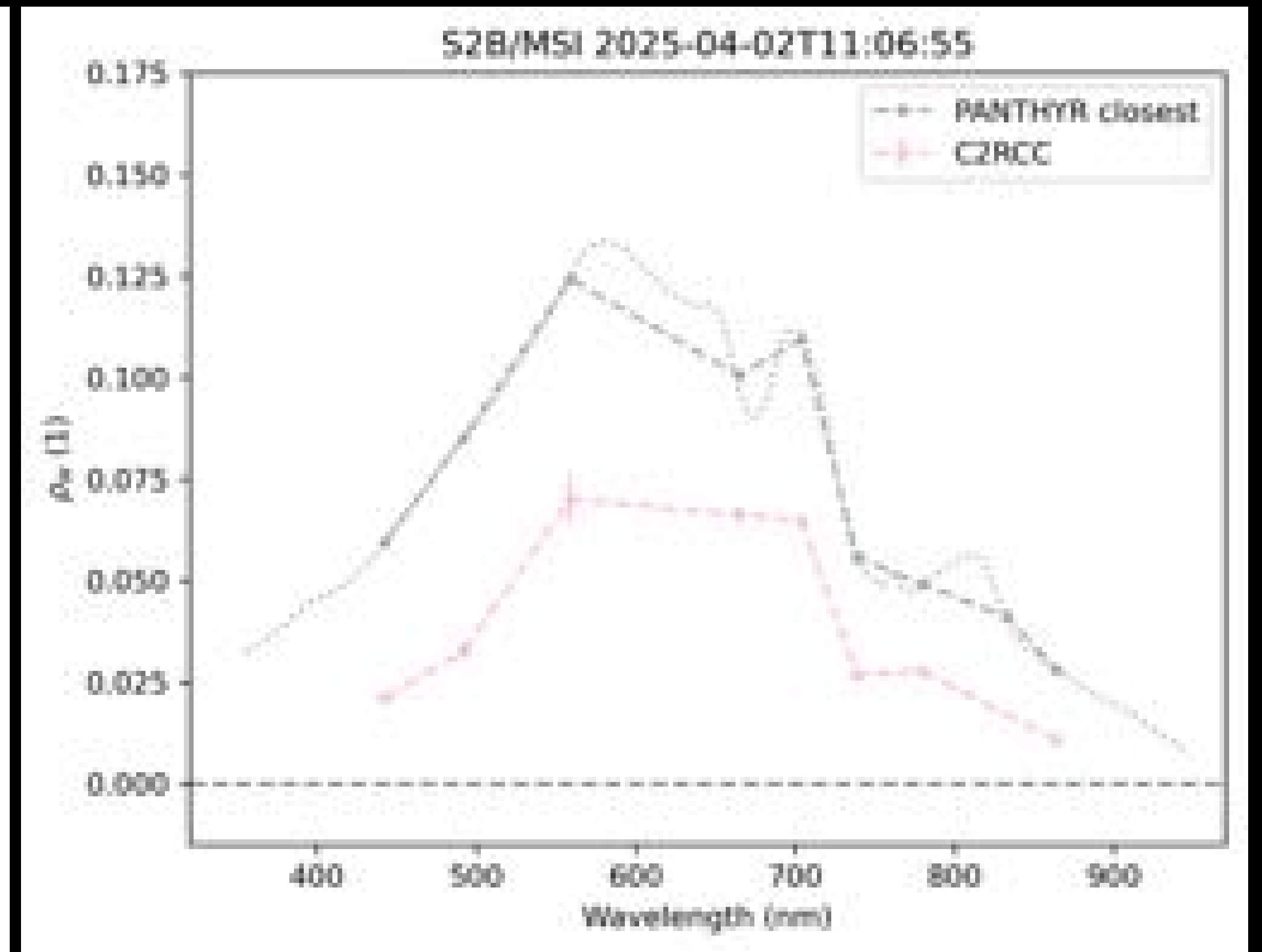


overcorrection, more bands output compared to l2gen

C2RCC

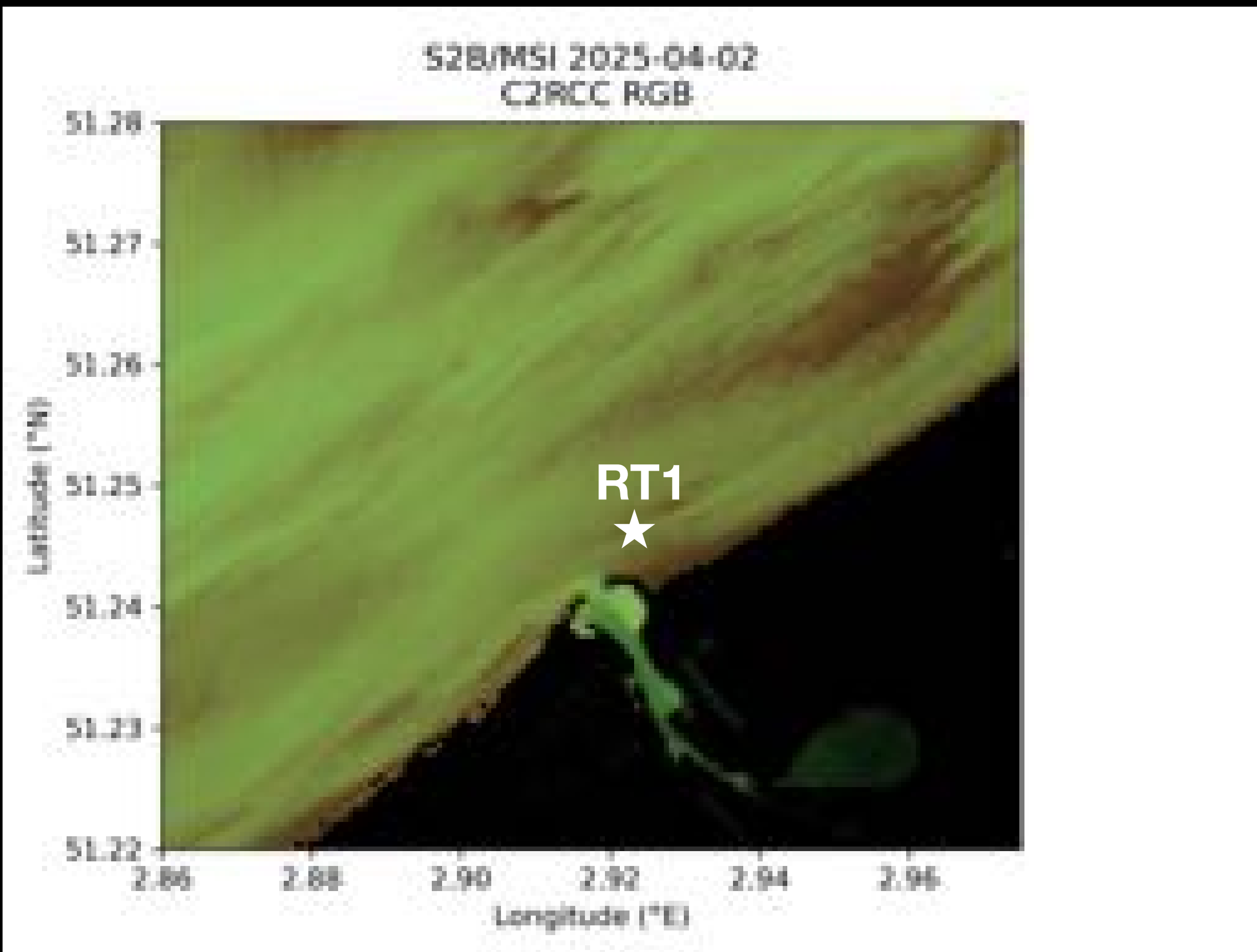


a bit brighter than I2gen/POLYMER, brown over most turbid areas

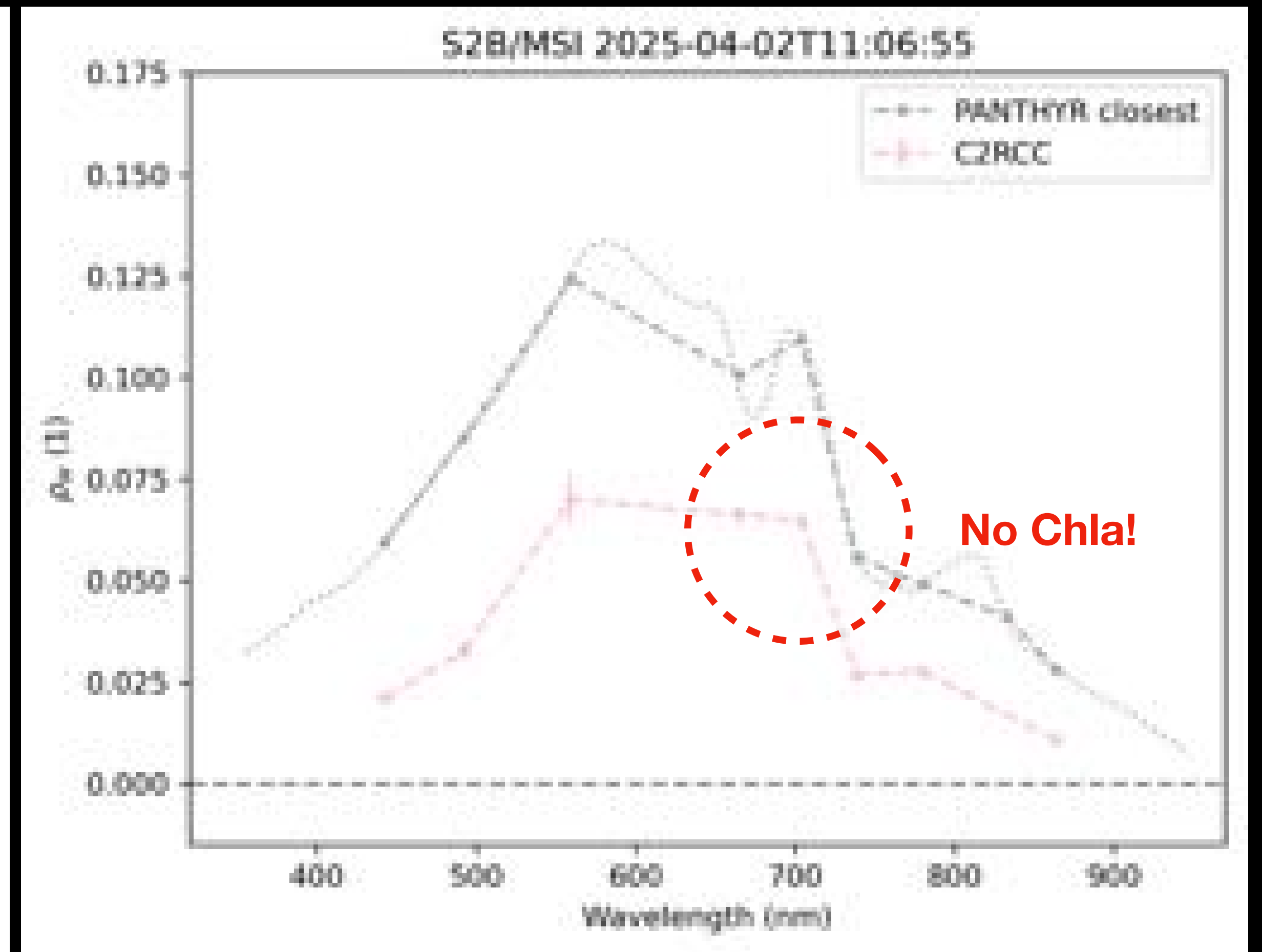


higher reflectance than I2gen/POLYMER, but red absorption feature has disappeared

C2RCC

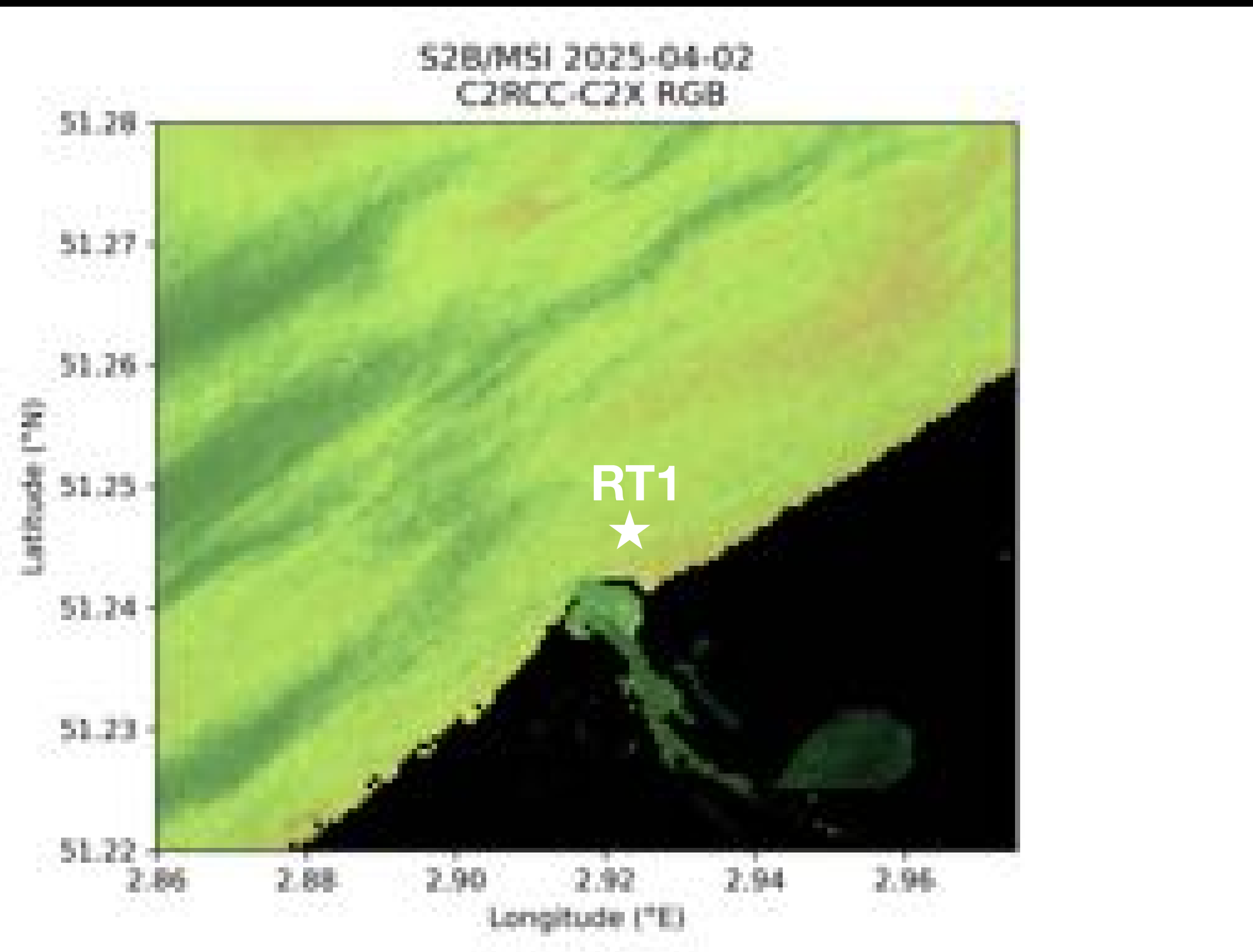


a bit brighter than I2gen/POLYMER, brown over most turbid areas

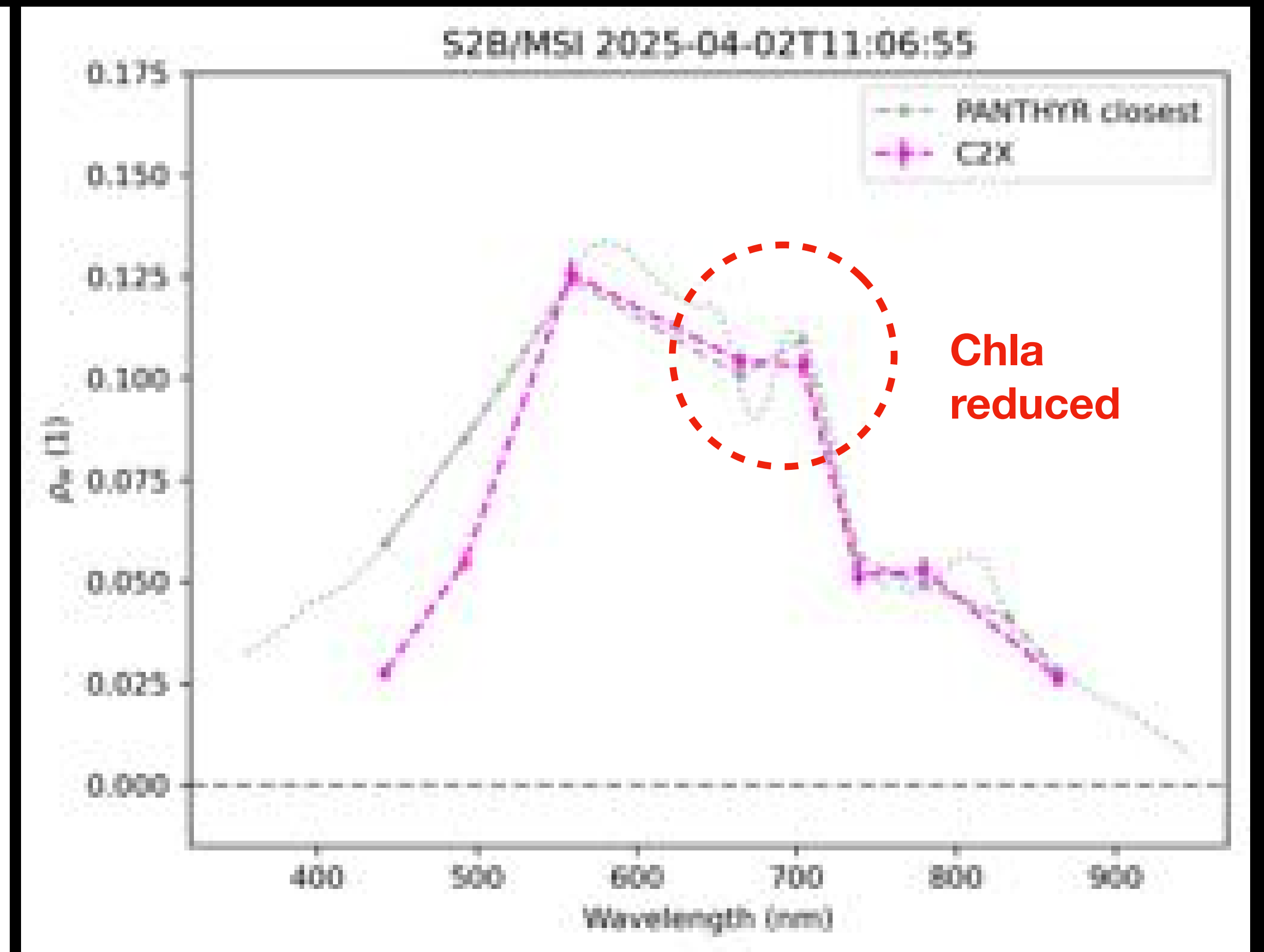


higher reflectance than I2gen/POLYMER, but red absorption feature has disappeared

C2RCC-C2X

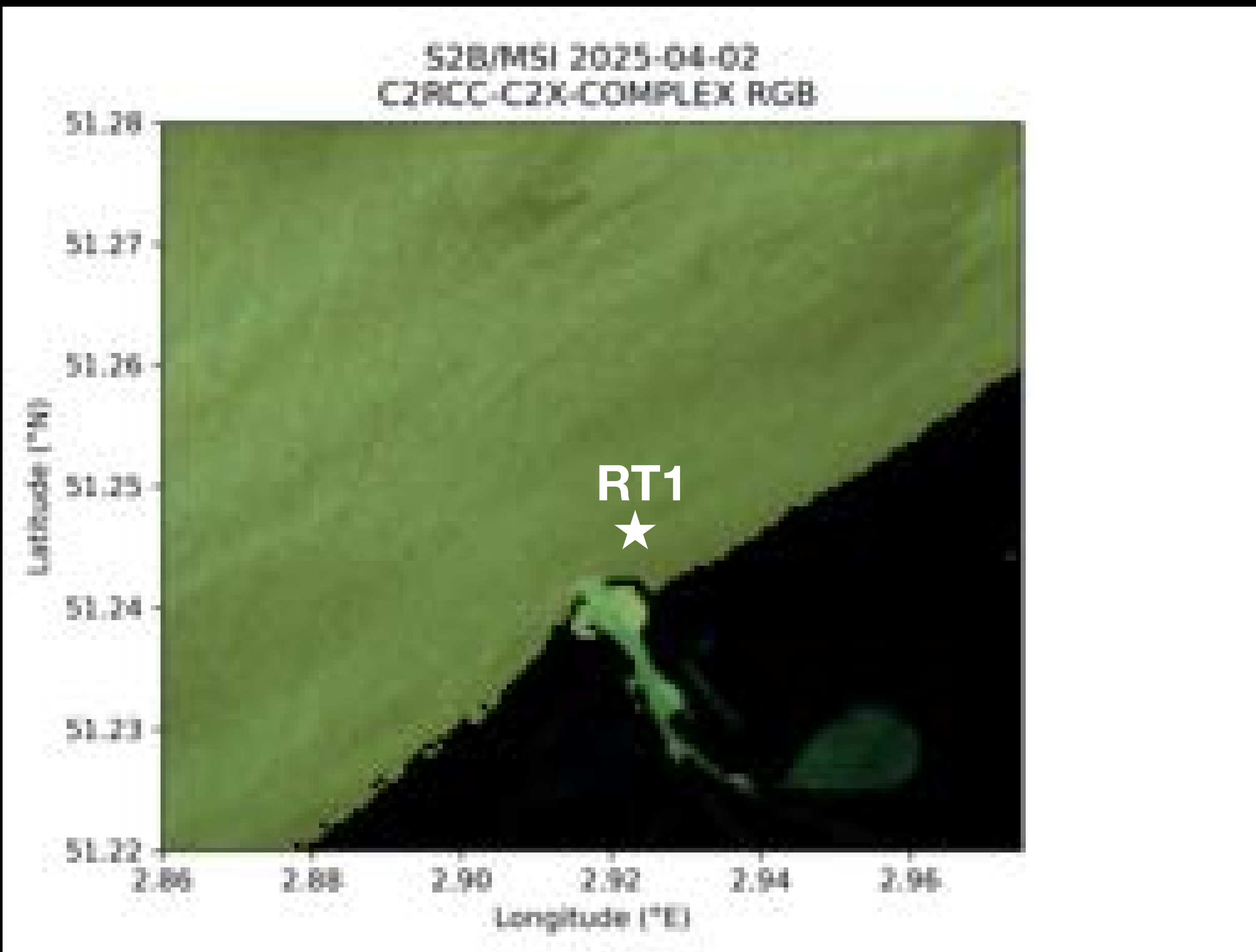


brighter than C2RCC, more noise, spatial variability reduced

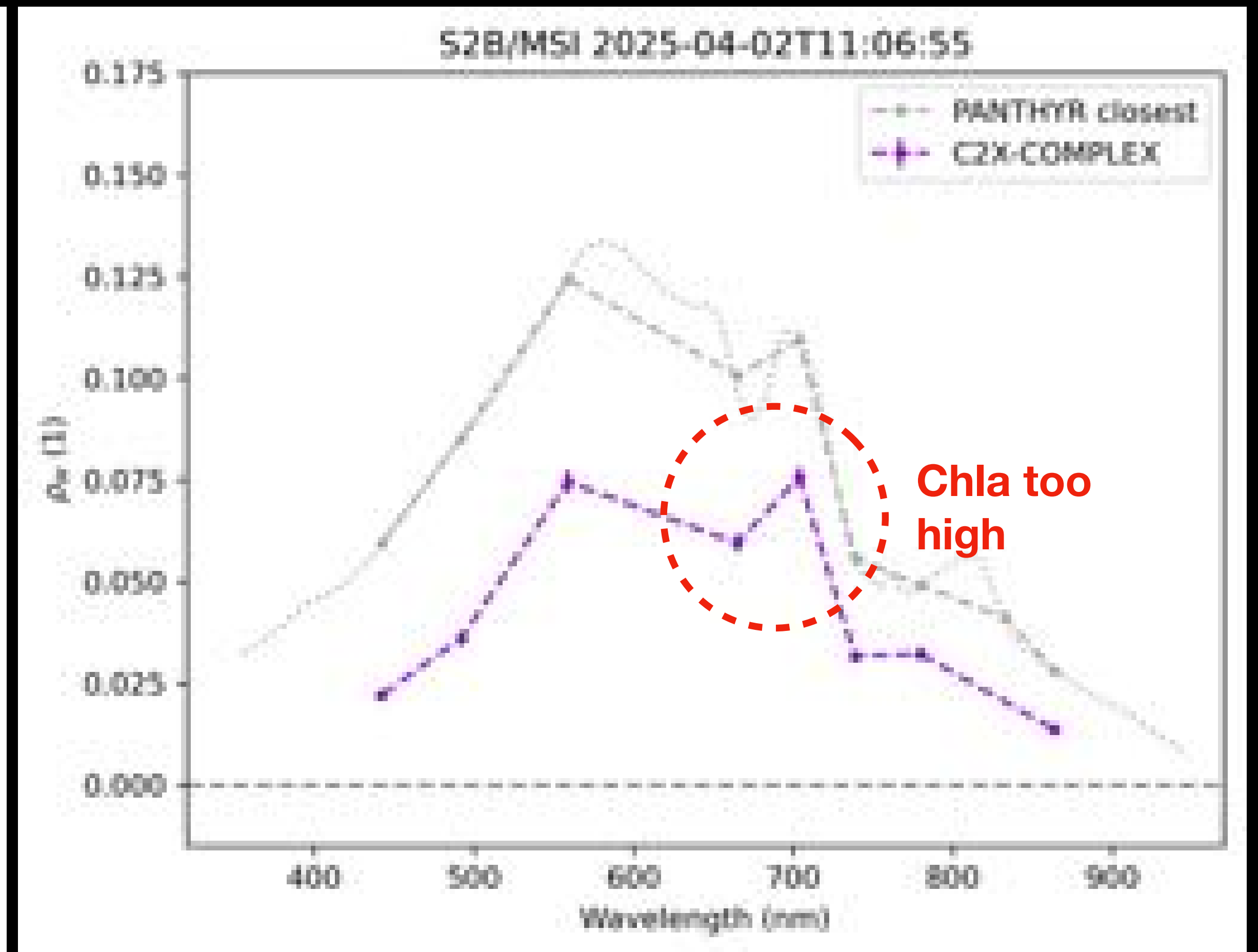


better fit compared to C2RCC , but red absorption feature missing

C2RCC-COMPLEX

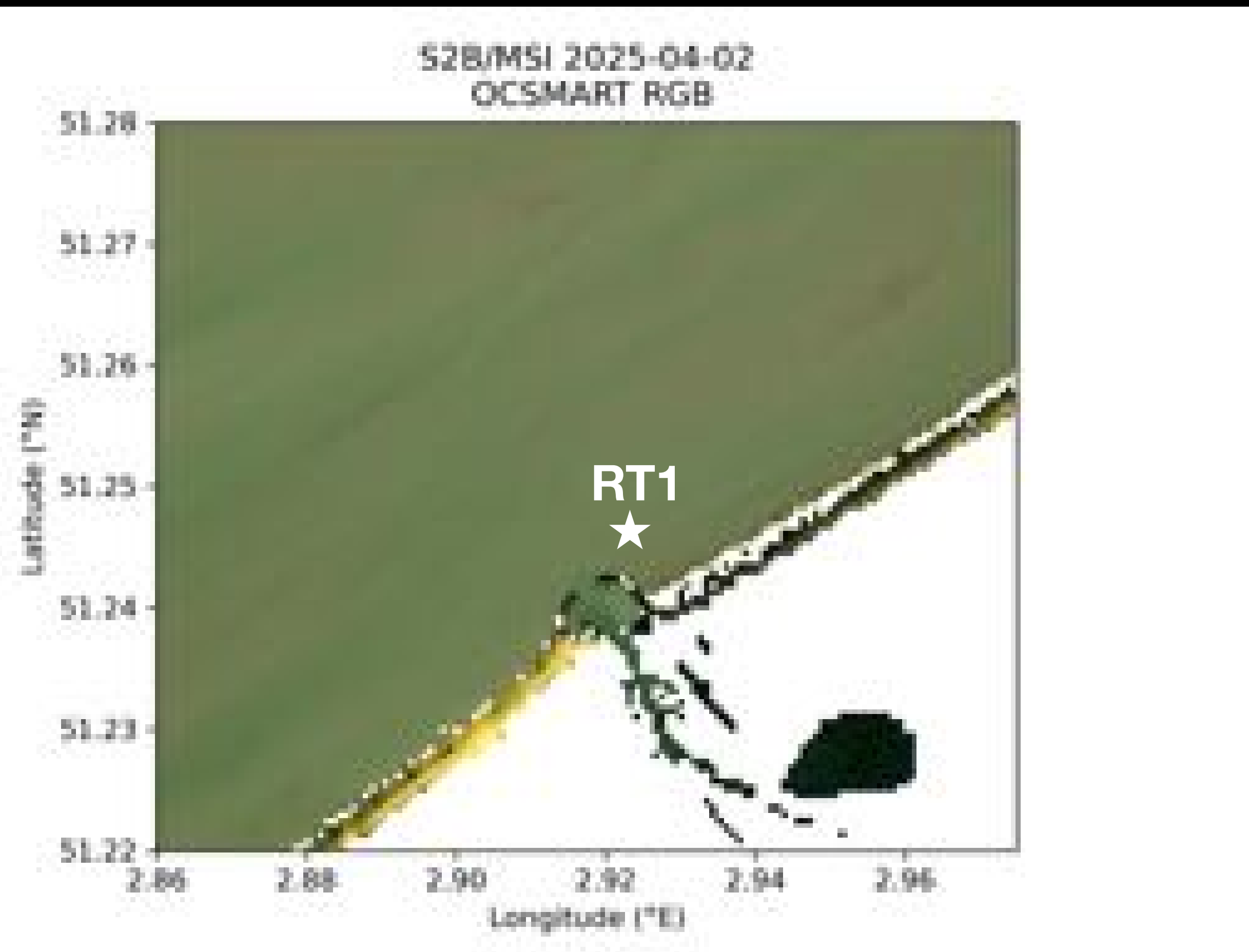


a bit darker than C2RCC, more noise, spatial variability reduced

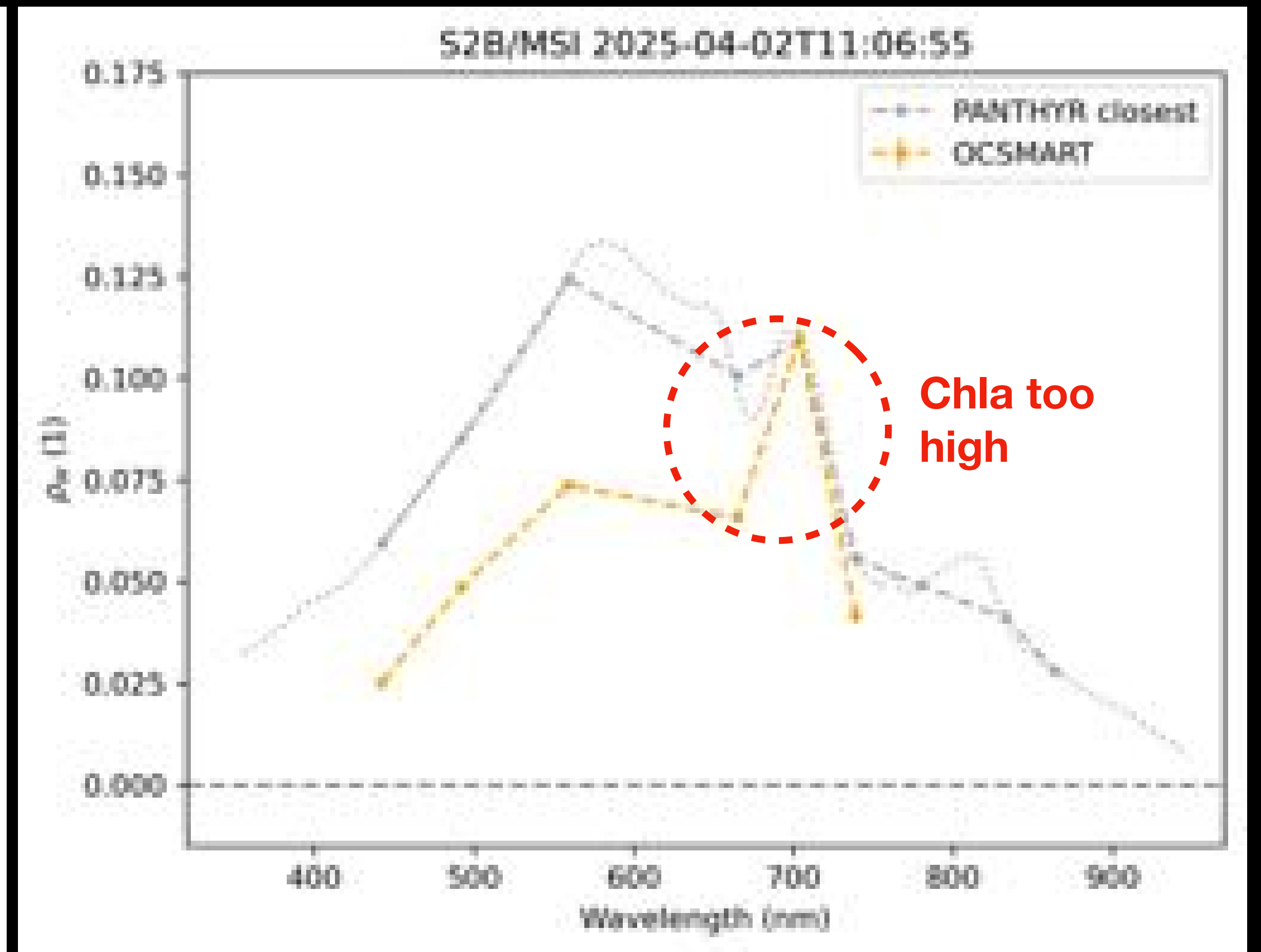


~ C2RCC and lower than C2X, red absorption feature reappears (too sharply?)

OC-SMART

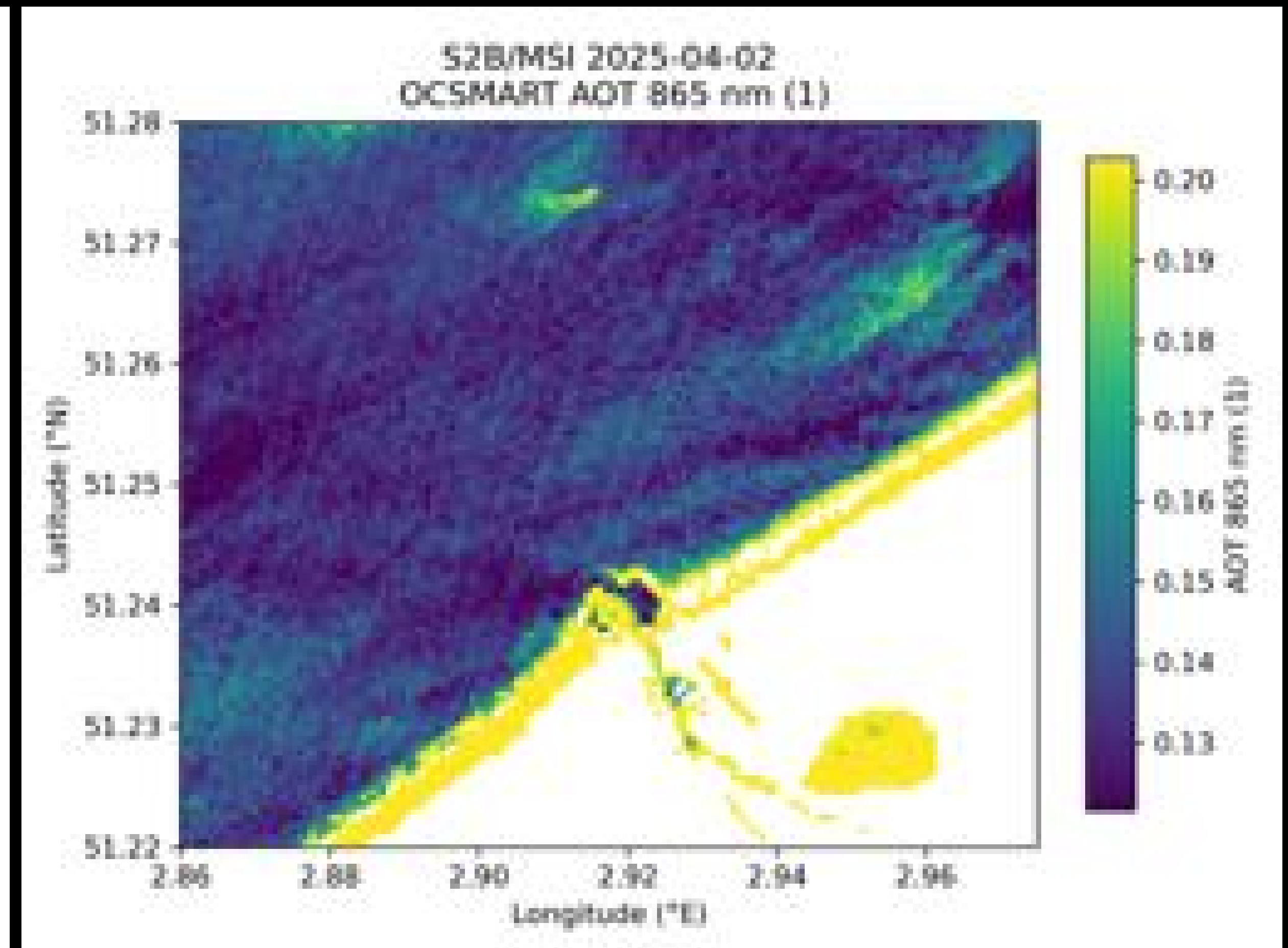
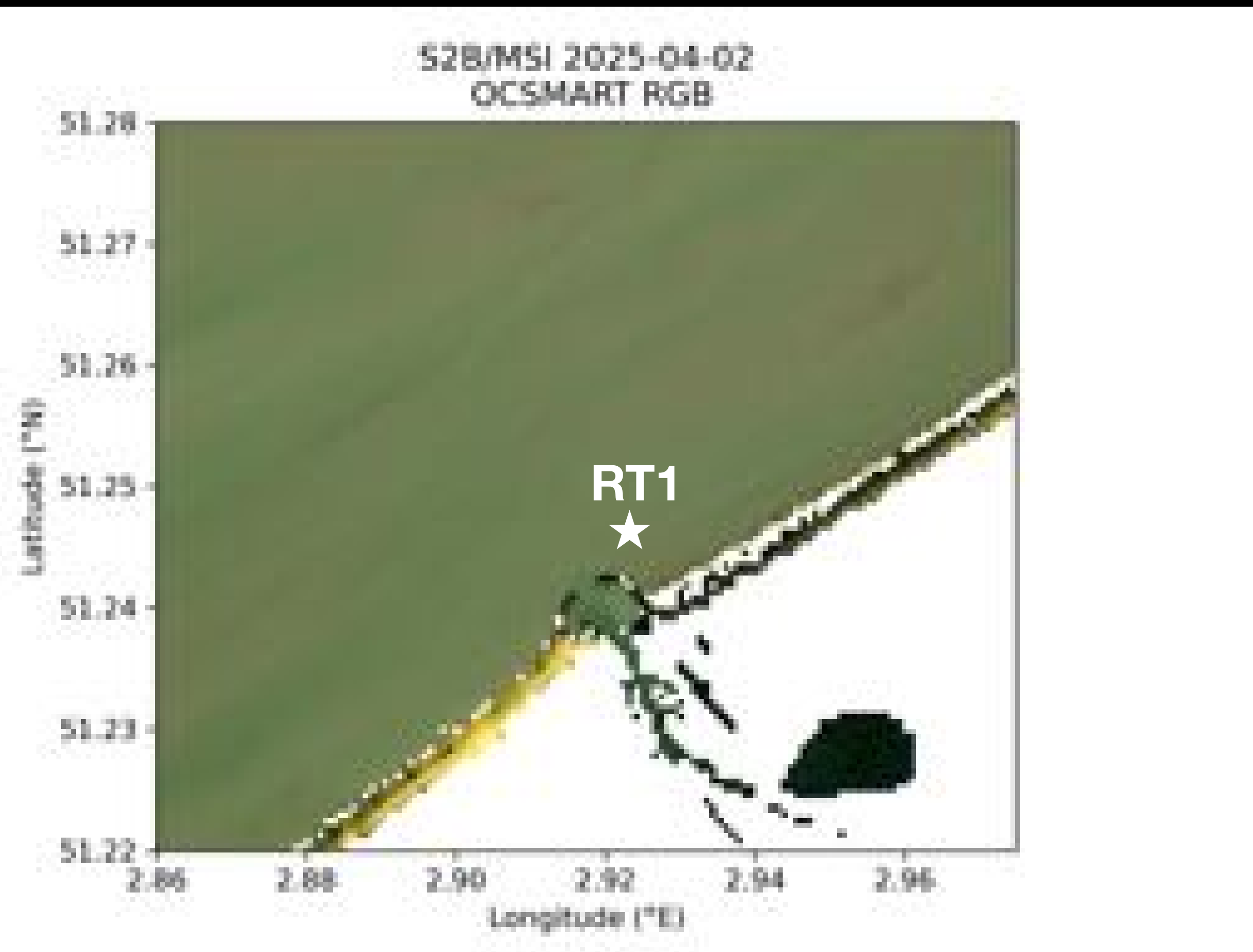


lower reflectance, brighter than POLYMER, less difference over most turbid waters



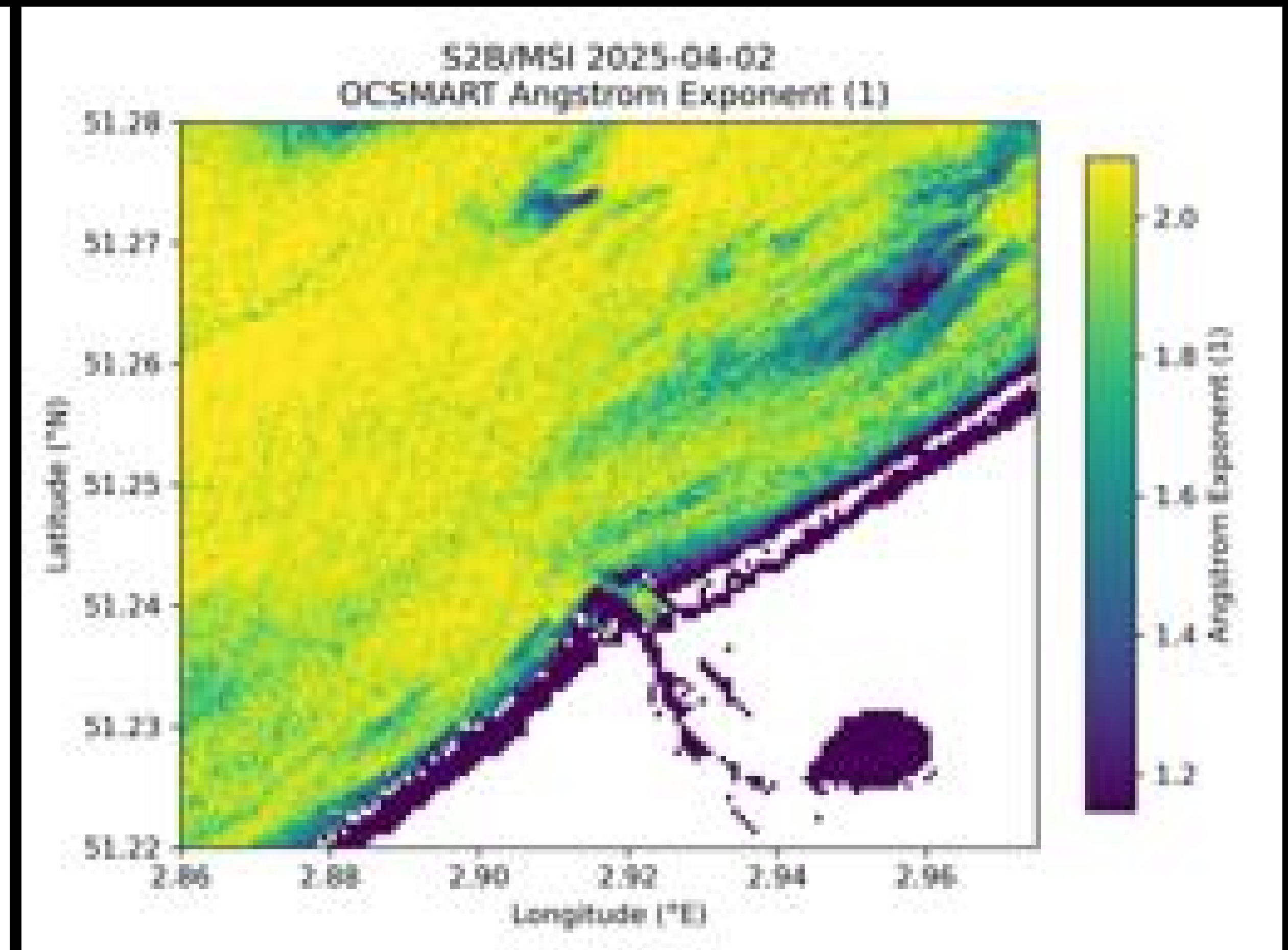
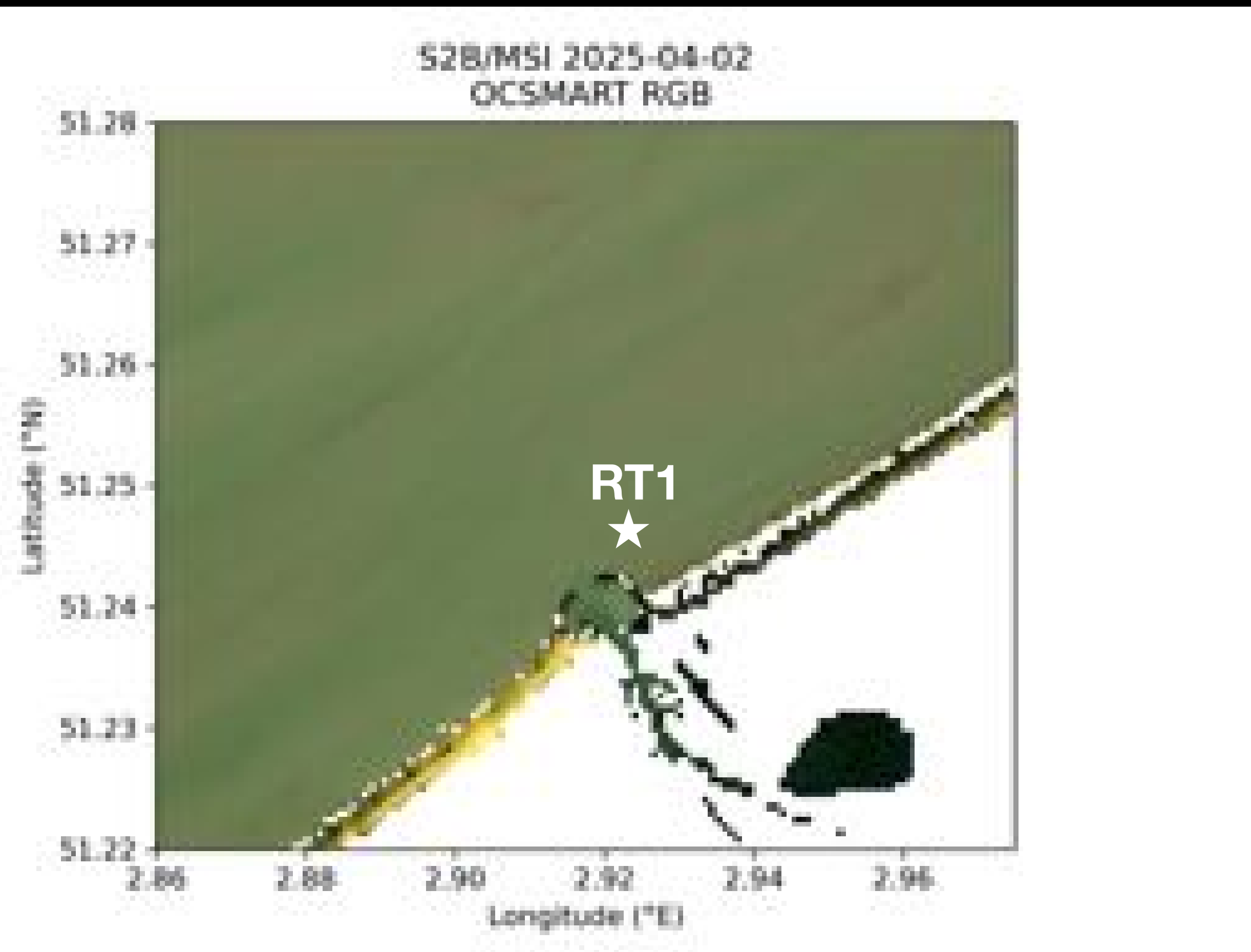
overcorrection in VIS , red absorption feature exaggerated

OC-SMART



aerosol optical depth ~ some water patterns, noisy,
high in the port and lake

OC-SMART

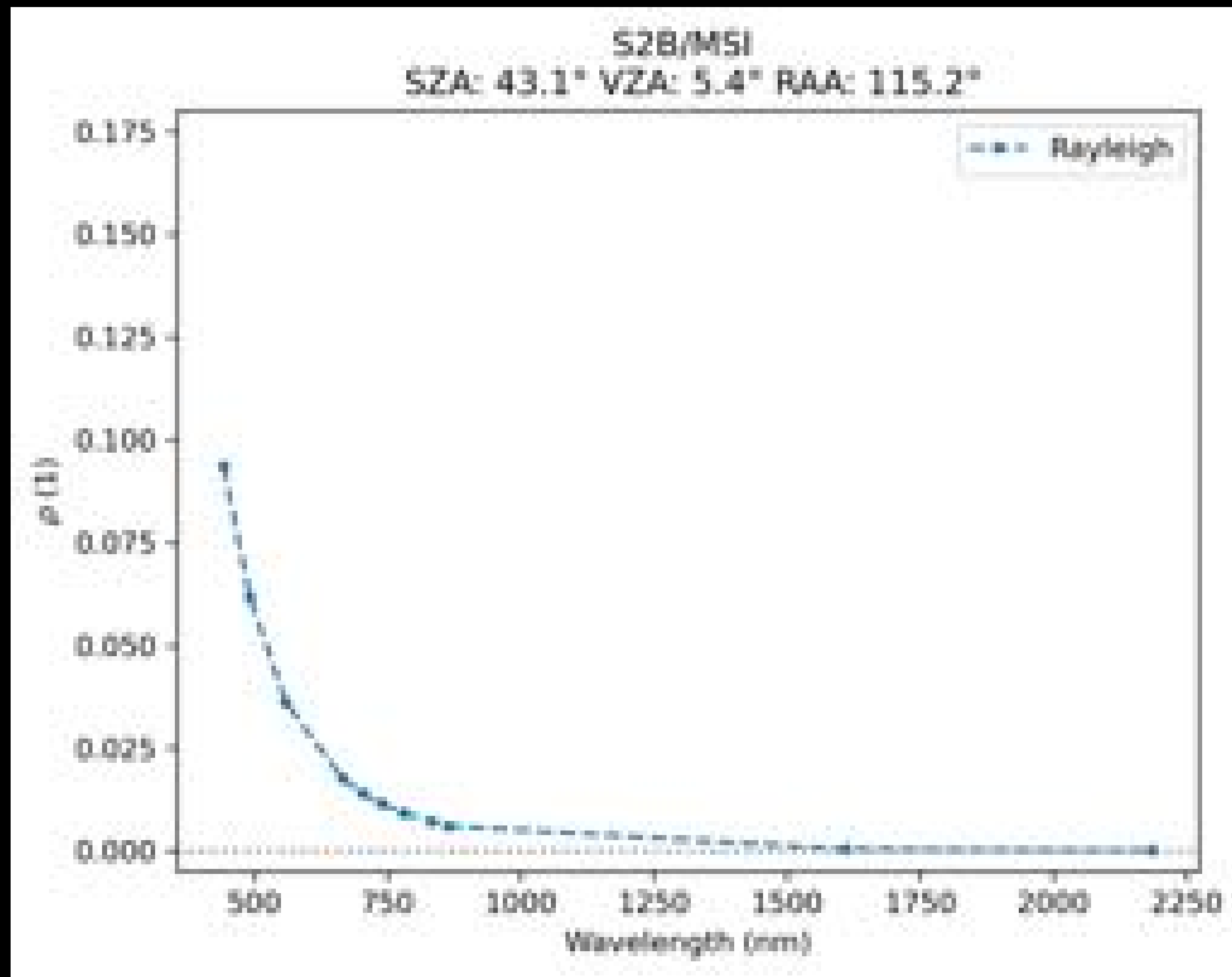


Angstrom ~ some water patterns, very low in port and lake, in some of the more turbid patches

Solutions?

No single algorithm seems to perform well everywhere, but for specific targets certain algorithms may be more suitable

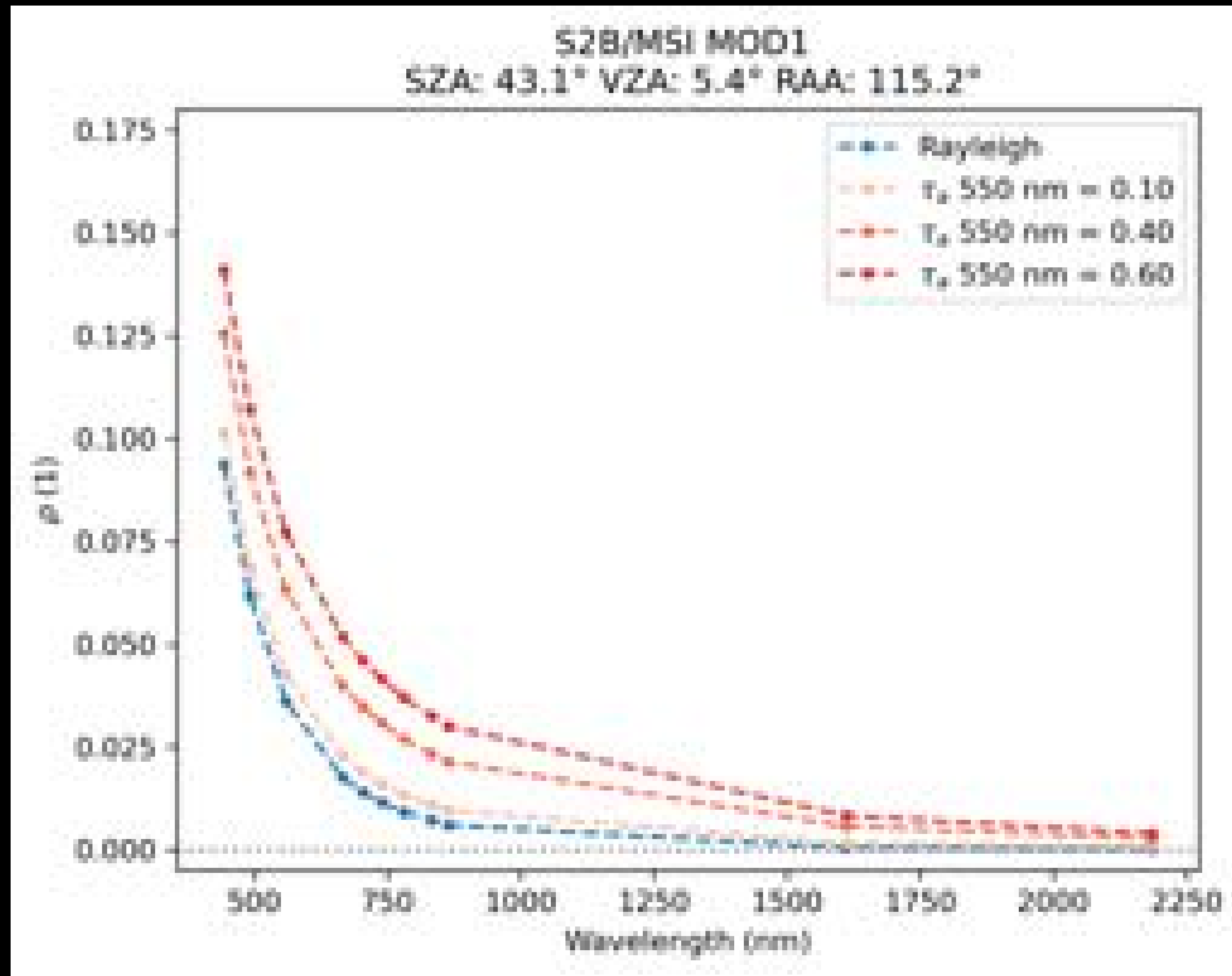
ACOLITE/DSF



1) extract geometry



ACOLITE/DSF

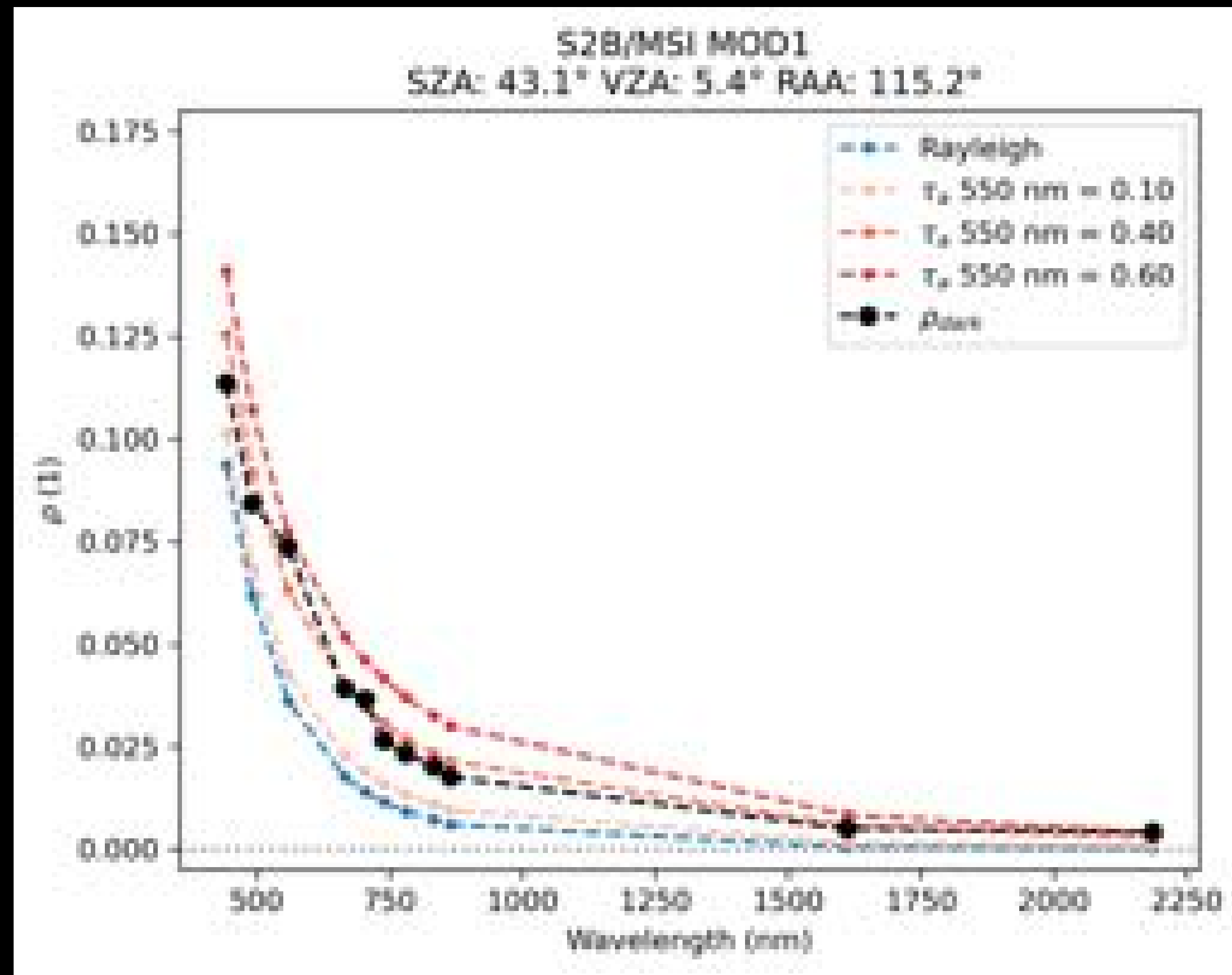


2) load LUTs



TOA

ACOLITE/DSF

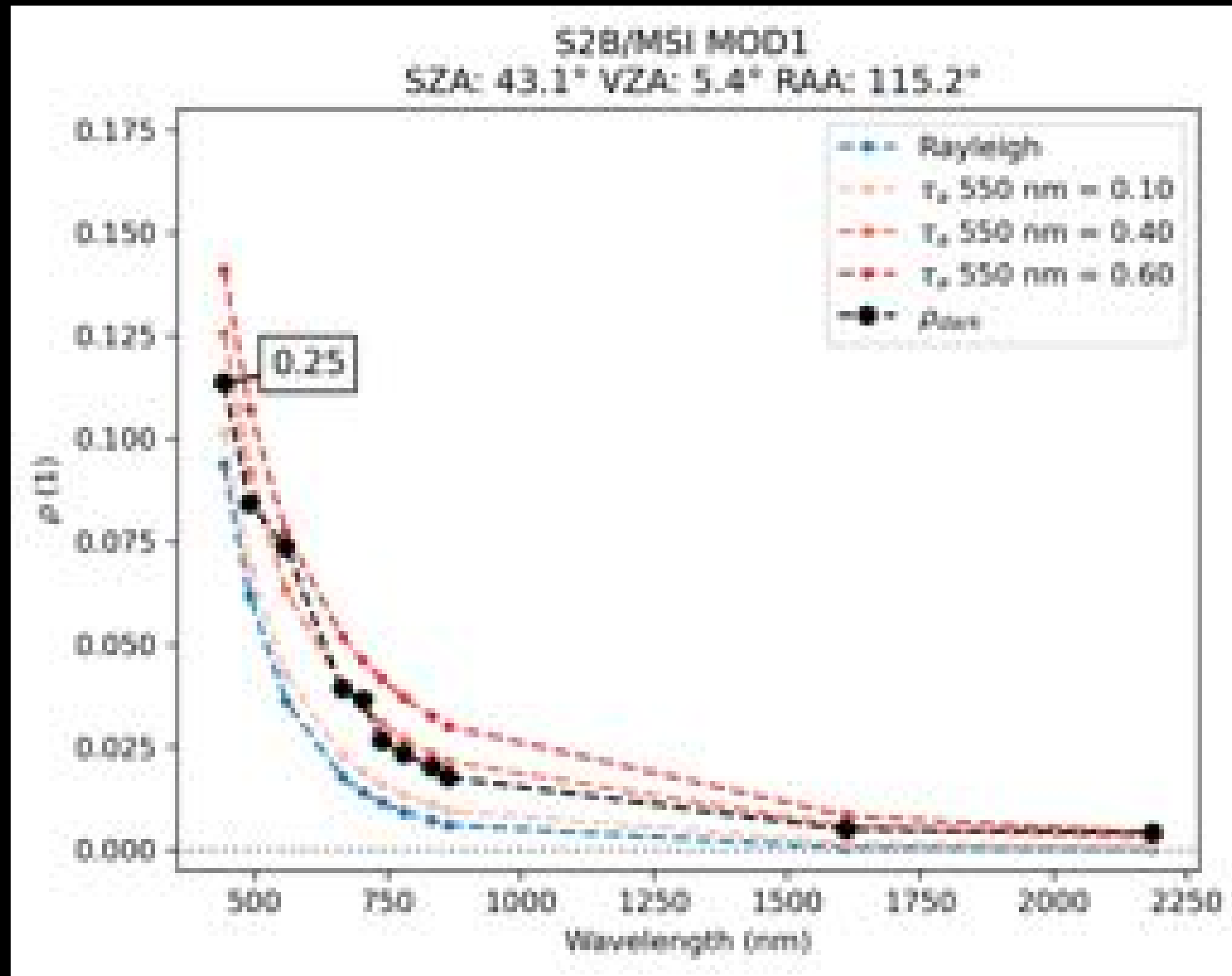


3) get pdark spectrum (here 2.275%)



TOA

ACOLITE/DSF

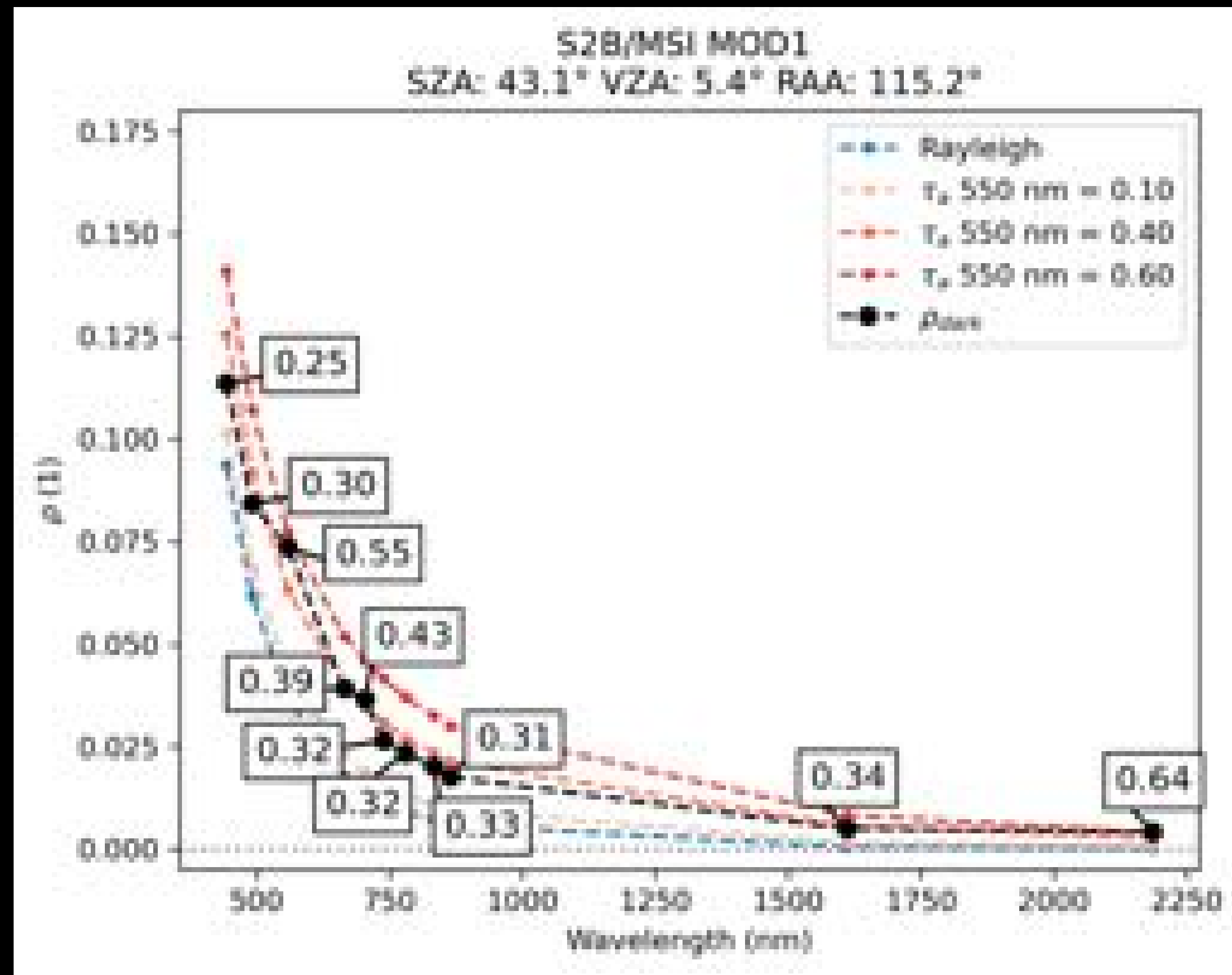


4) estimate τ_a for ρ_{dark}



TOA

ACOLITE/DSF

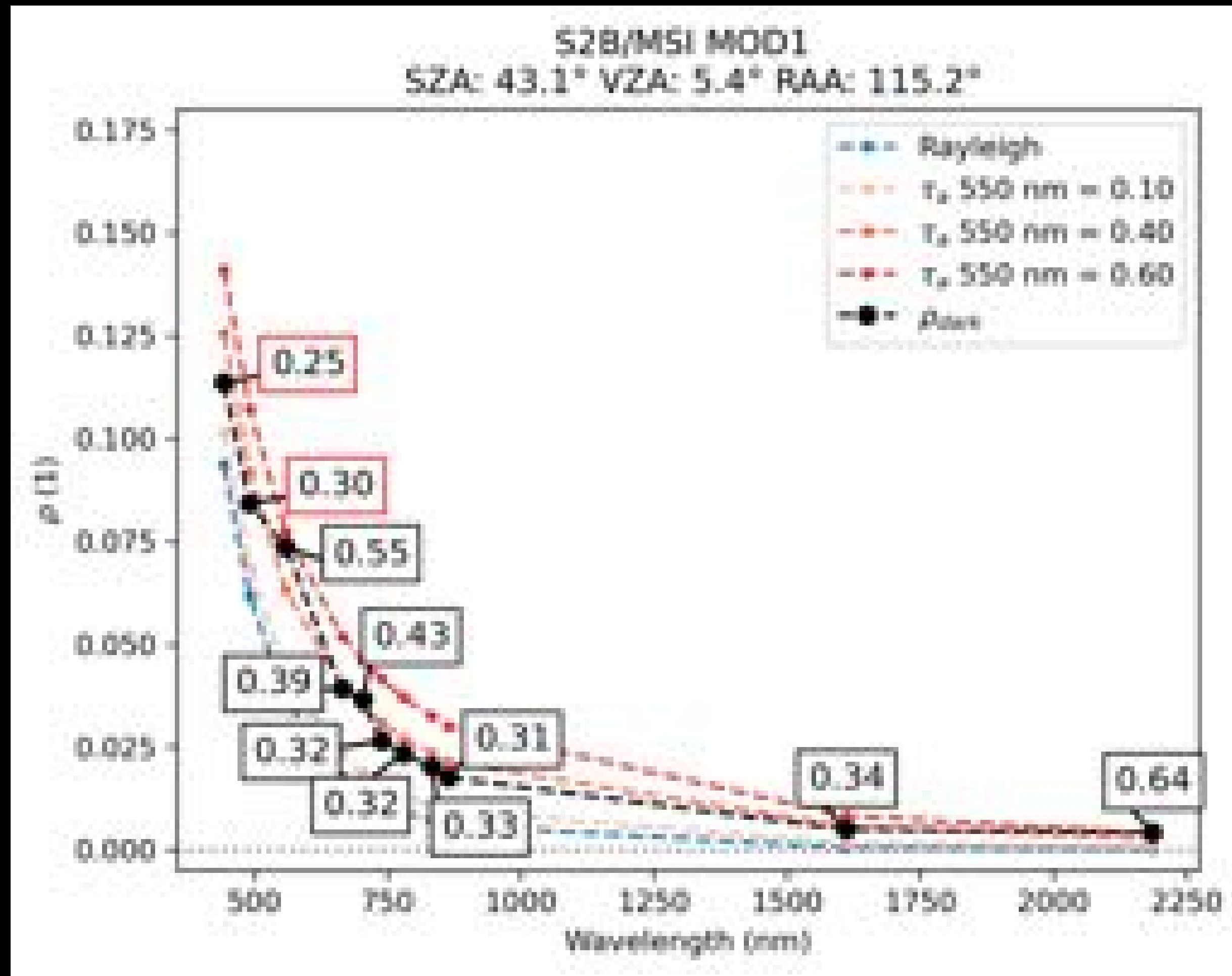


4) estimate τ_a for ρ_{dark}



TOA

ACOLITE/DSF

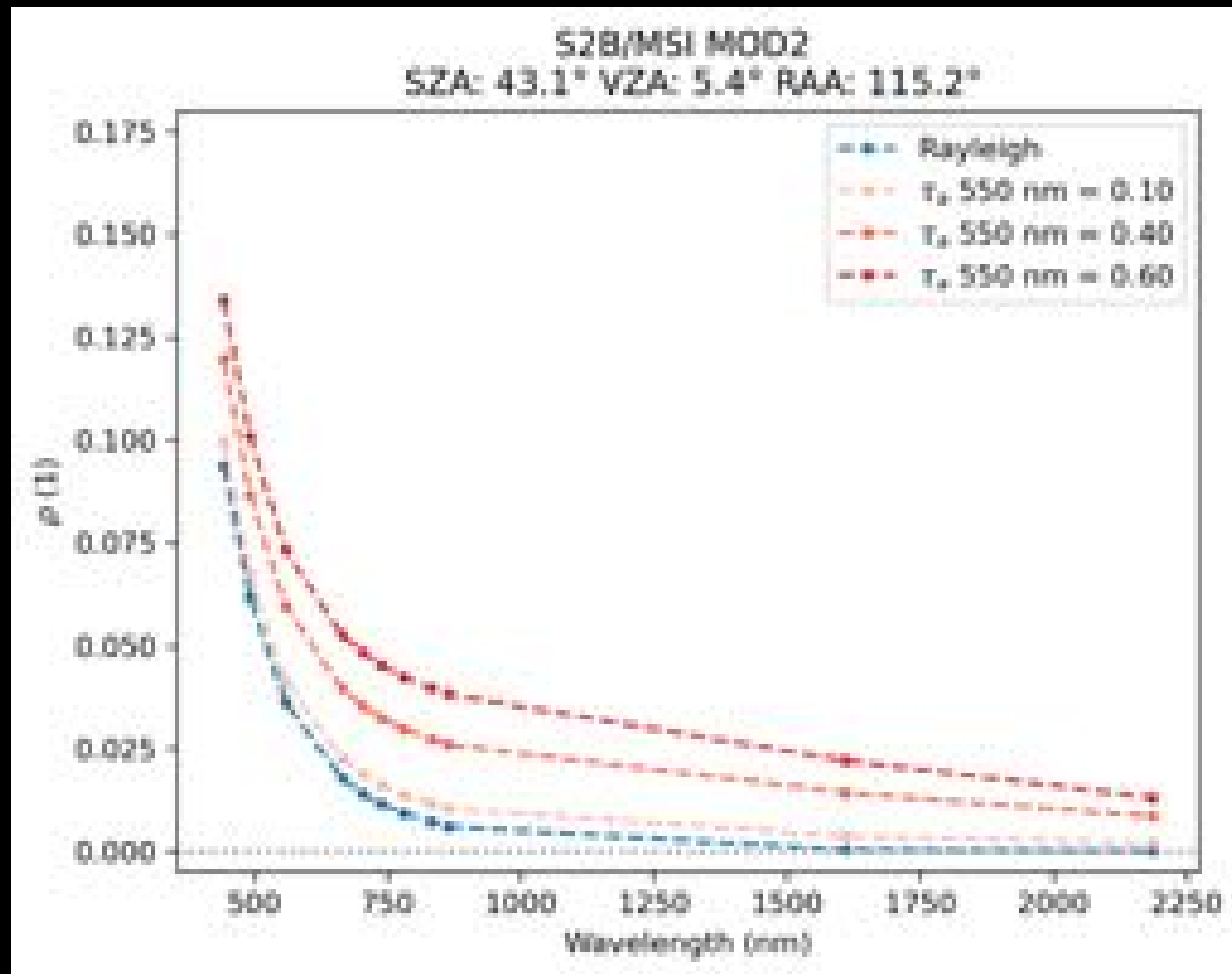


5) find lowest τ_a - here B1 and B2



TOA

ACOLITE/DSF

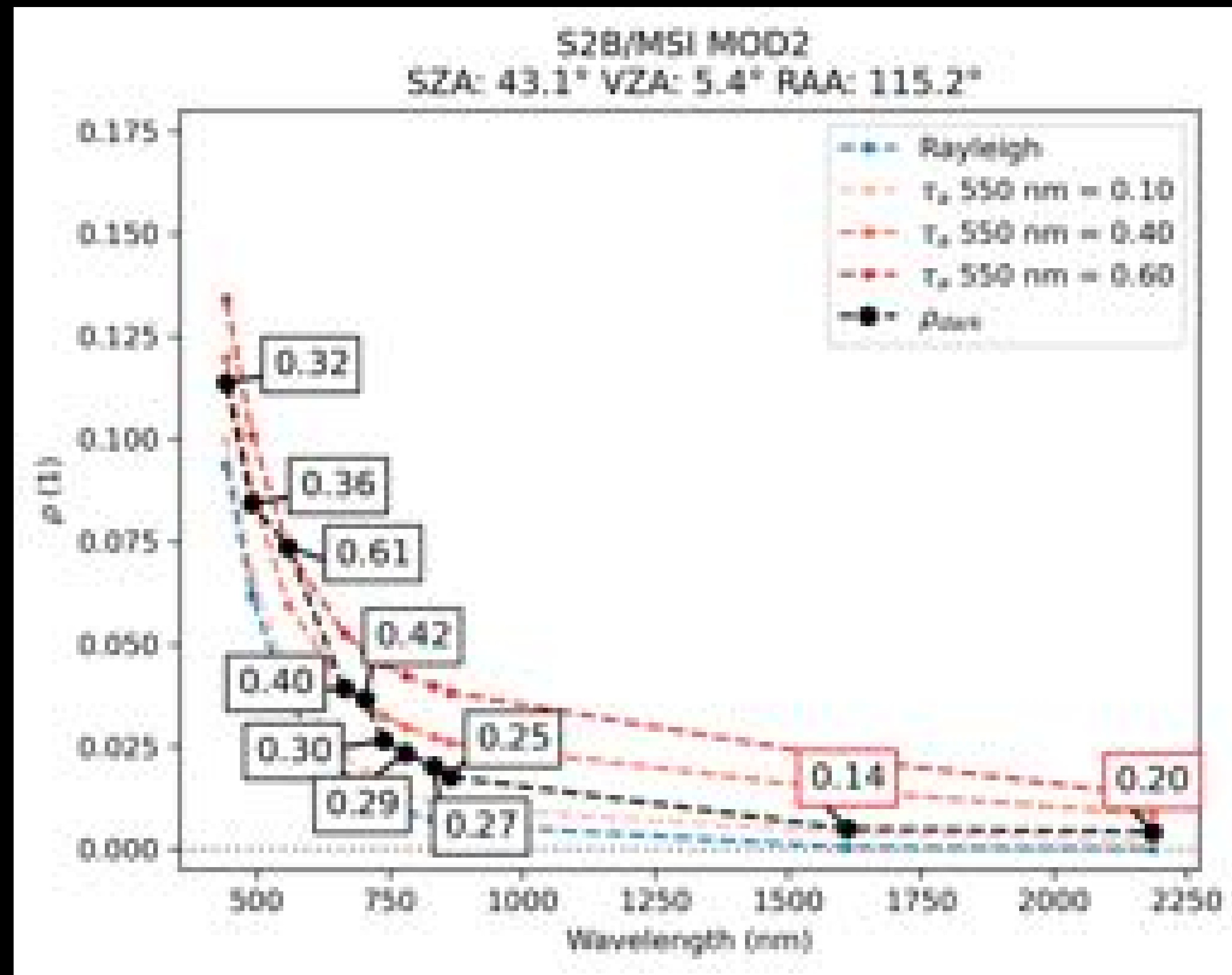


6) repeat for other model



TOA

ACOLITE/DSF



6) here B11 and B12



TOA

ACOLITE/DSF

$$\frac{\rho_t}{T_g} = \rho_{path} + \frac{\rho_s \cdot T_d T_u}{1 - \rho_s \cdot S}$$

TOA reflectance

Surface reflectance

Two-way atmospheric transmittance

Gas transmittance (O₂, O₃, H₂O)

Atmospheric path reflectance (Rayleigh+aerosol)

Spherical albedo of the atmosphere

6SV formulation e.g. Vermote et al. 1997

7) select model, and compute ρ_s



TOA

ACOLITE/DSF

TOA reflectance

Surface reflectance

Two-way atmospheric transmittance

$$\frac{\rho_t}{T_g} = \rho_{path} + \frac{\rho_s \cdot T_d T_u}{1 - \rho_s \cdot S}$$

Gas transmittance
(O₂, O₃, H₂O)

Atmospheric path
reflectance
(Rayleigh+aerosol)

Spherical albedo
of the atmosphere

6SV formulation e.g. Vermote et al. 1997

7) select model, and compute ρ_s



BOA

ACOLITE/DSF

$$\frac{\rho_t}{T_g} = \rho_{path} + \frac{\rho_s \cdot T_d T_u}{1 - \rho_s \cdot S}$$

low contrast / homogeneous surface: $\rho_e = \rho_s$

ACOLITE/DSF

$$\frac{\rho_t}{T_g} = \rho_{path} + T_d \cdot T_u \cdot \frac{\rho_s}{1 - \rho_s \cdot S}$$

low contrast / homogeneous surface: $\rho_e = \rho_s$

ACOLITE/DSF

$$\frac{\rho_t}{T_g} = \rho_{path} + T_d \cdot \frac{T_u^{dir} \cdot \rho_s}{1 - \rho_e \cdot S} + T_d \cdot \frac{T_u^{dif} \cdot \rho_e}{1 - \rho_e \cdot S}$$

low contrast / homogeneous surface: $\rho_e = \rho_s$

ACOLITE/RAdCor

$$\frac{\rho_t}{T_g} = \rho_{path} + T_d \cdot \frac{T_u^{dir} \cdot \rho_s}{1 - \rho_e \cdot S} + T_d \cdot \frac{T_u^{dif} \cdot \rho_e}{1 - \rho_e \cdot S}$$

high contrast / heterogeneous surface: $\rho_e \neq \rho_s$

ACOLITE/RAdCor

$$\frac{\rho_t}{T_g} = \rho_{path} + T_d \cdot \frac{\rho_s}{1 - \rho_s \circledast SAF} \circledast PSF$$

high contrast / heterogeneous surface: $\rho_e \neq \rho_s$

after some “generous approximations”

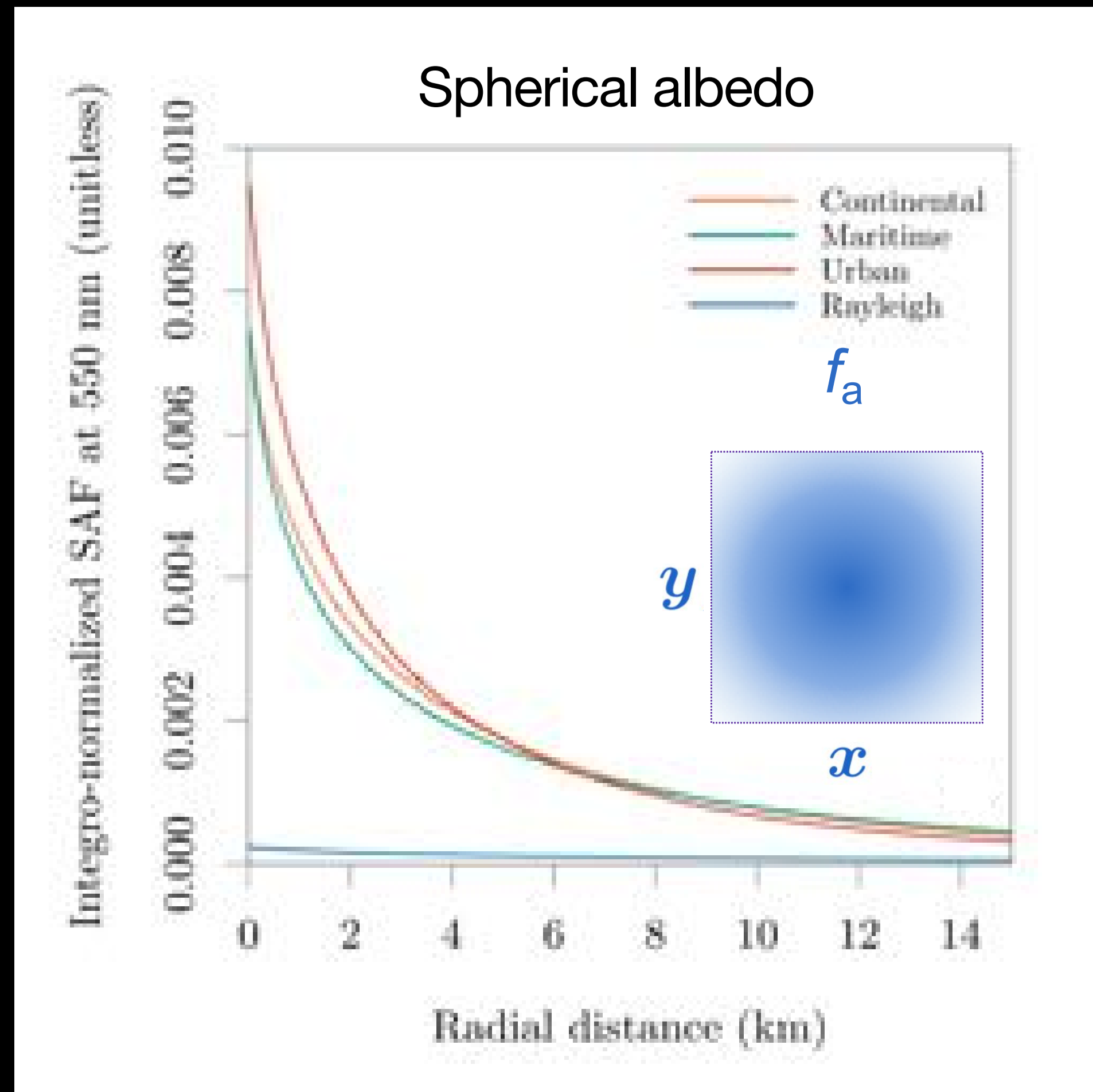
$\circledast$ image convolution

SAF spherical albedo function

PSF point spread function

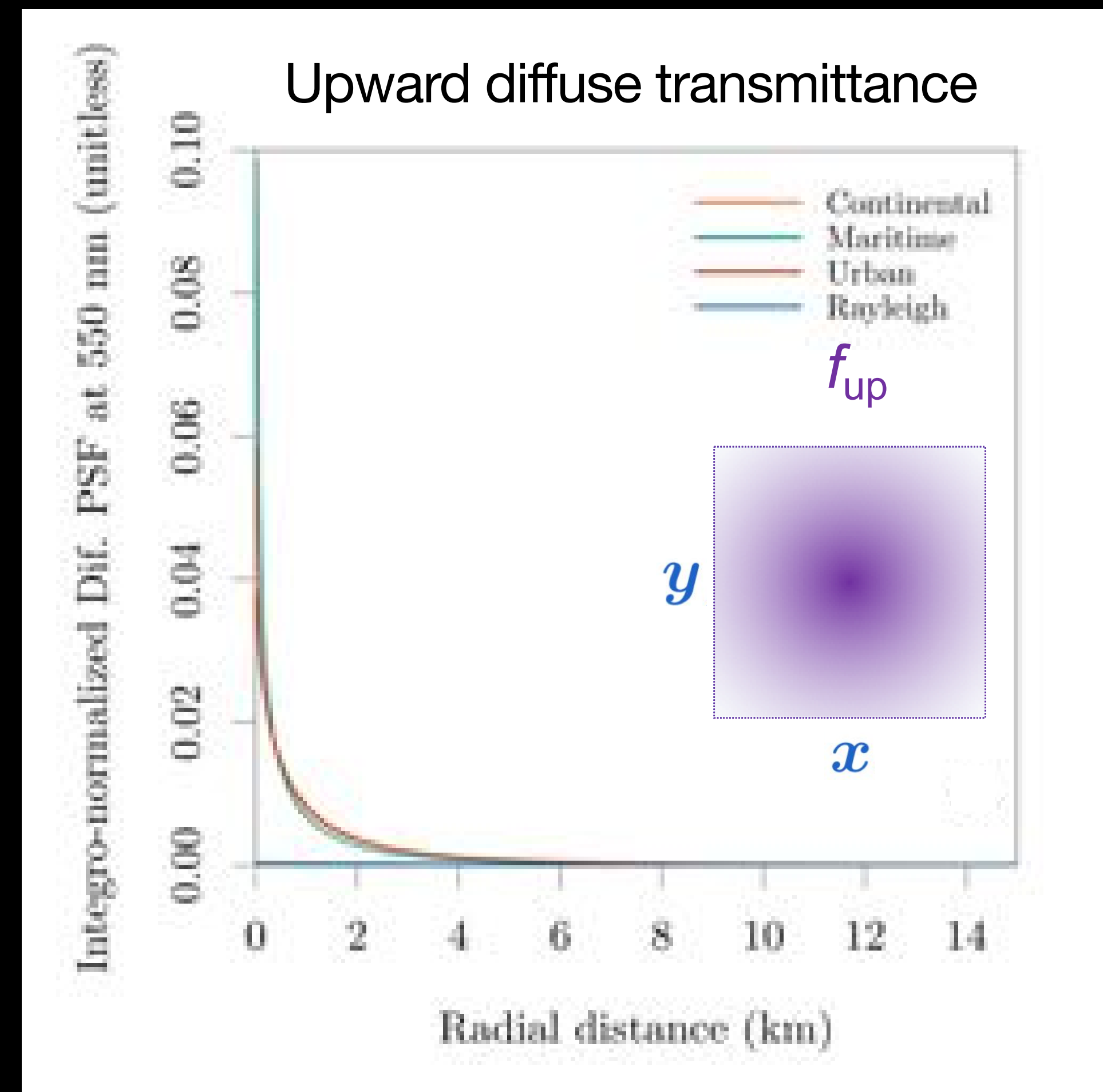
ACOLITE/RAdCor

⊗ SAF



(default kernel size 5 km)

⊗ PSF



ACOLITE/RAdCor

ρ_e estimate RGB



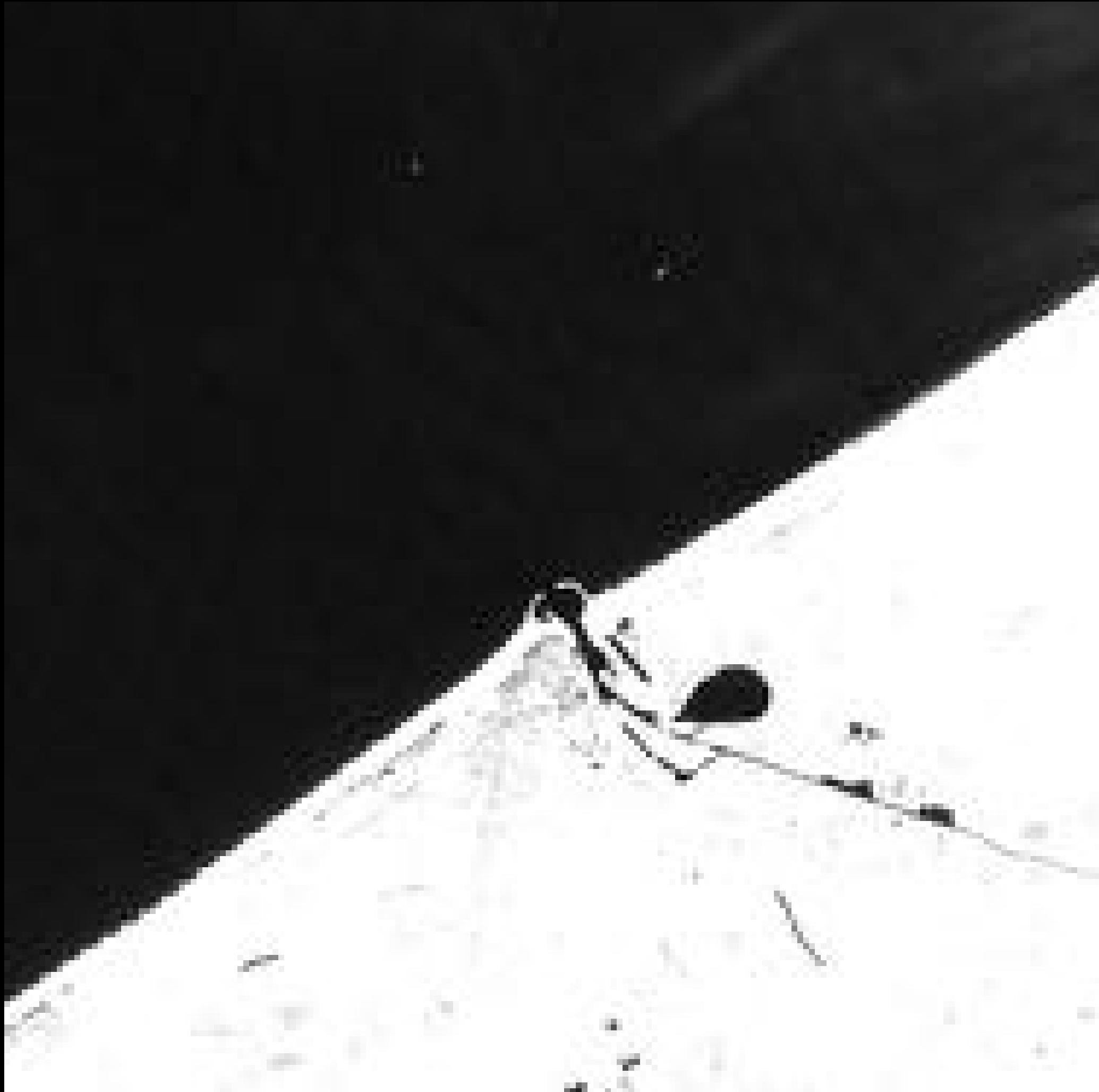
homogeneous



heterogeneous

ACOLITE/RAdCor

ρ_e estimate NIR



homogeneous

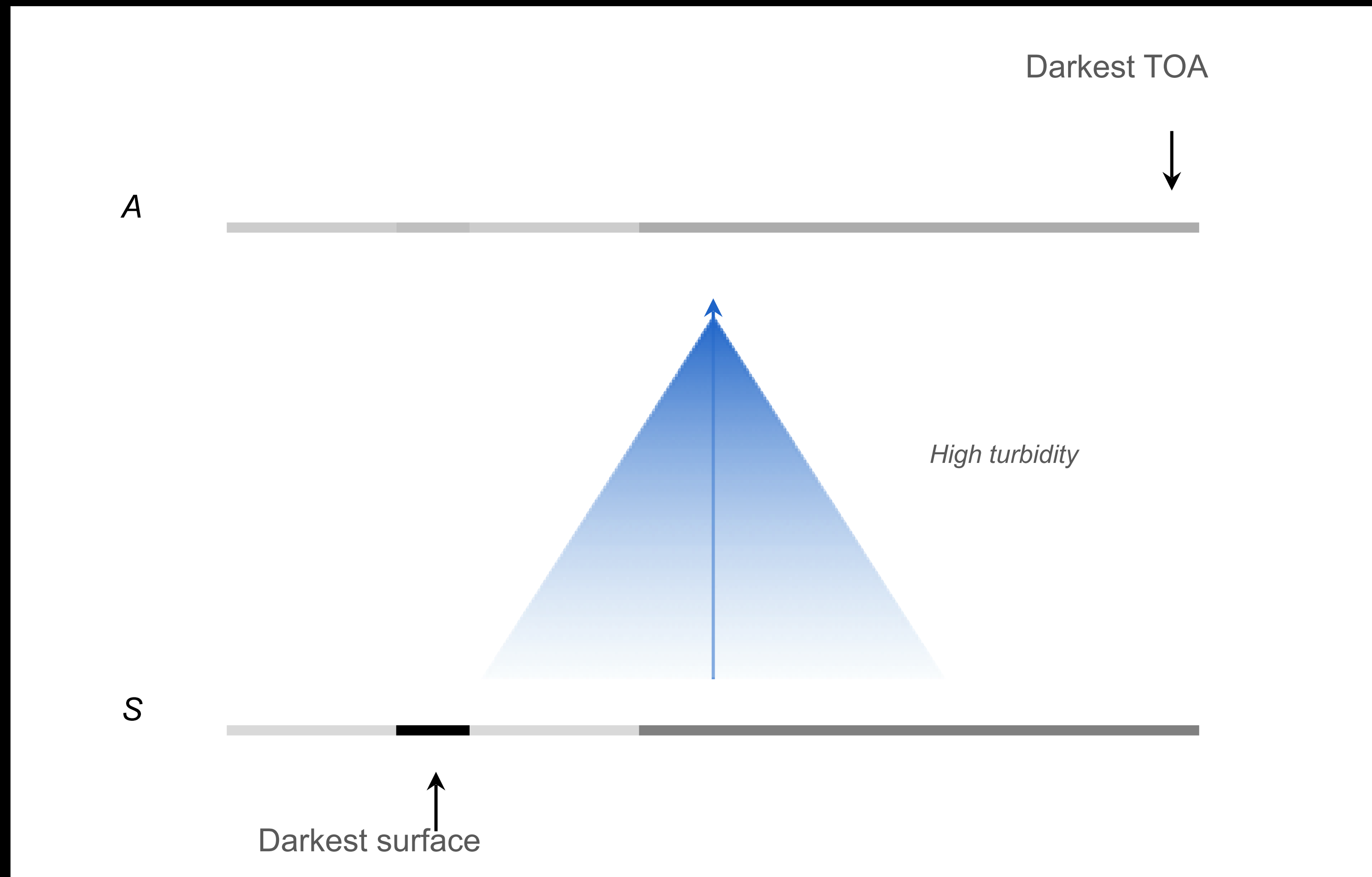


heterogeneous

ACOLITE/RAdCor

DSF estimation ~ ρ_{dark} at TOA

TSDSF estimation ~ ρ_{dark} at BOA



ACOLITE/RAdCor

TSDSF estimation ~ ρ_{dark} at BOA

1) compute hypothetical quantity ρ_t^{HYP}

TOA if all upward transmittance diffuse, estimated ρ_t for high aerosol optical depth ($\tau_{a, 550} = 1.0$) :

$$\rho_t^{HYP} = \rho_t \circledast PSF$$

For dark pixels at surface ($\rho_s = 0$) the ratio determines the diffuse fraction of the upward transmittance:

$$\frac{\rho_t - \rho_{path}}{\rho_t^{HYP} - \rho_{path}} = \frac{T_u^{dif}}{T_u^{tot}}$$

ACOLITE/RAdCor

TSDSF estimation ~ ρ_{dark} at BOA

2) detection of dark pixels at surface using heuristic

$$\min\left[\frac{\rho_t \cdot \rho_t}{\rho_t^{\text{HYP}}}\right]$$

The ratio of TOA to hypothetical quantity is proportional to the ratio of target to environmental reflectance.

Small values indicate upscaling adjacency, large values indicate downscaling adjacency, scaled by TOA to account for absolute reflectance.

ACOLITE/RAdCor

TSDSF estimation ~ ρ_{dark} at BOA

- 3) find τ_a that minimises difference between modeled and estimated diffuse fraction

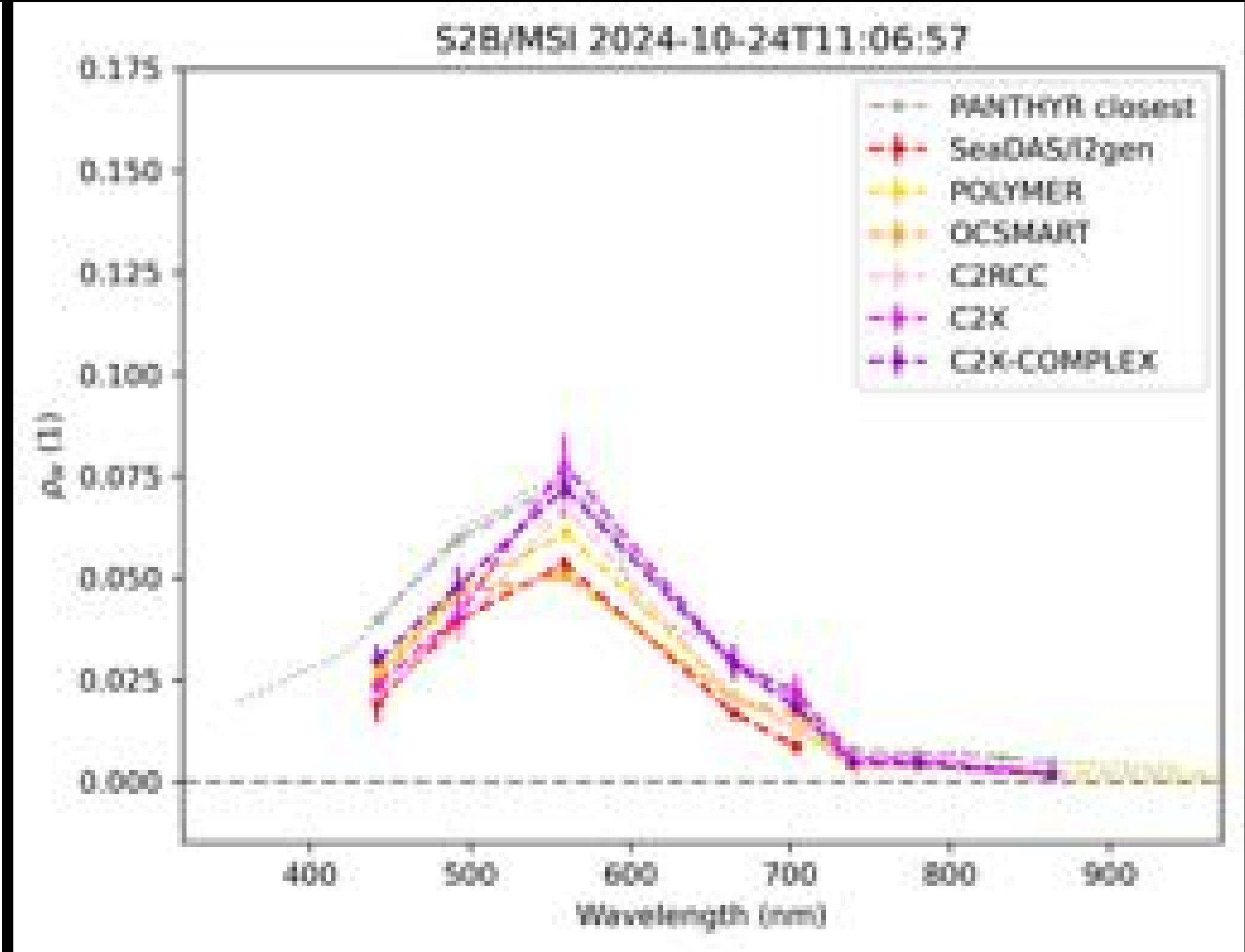
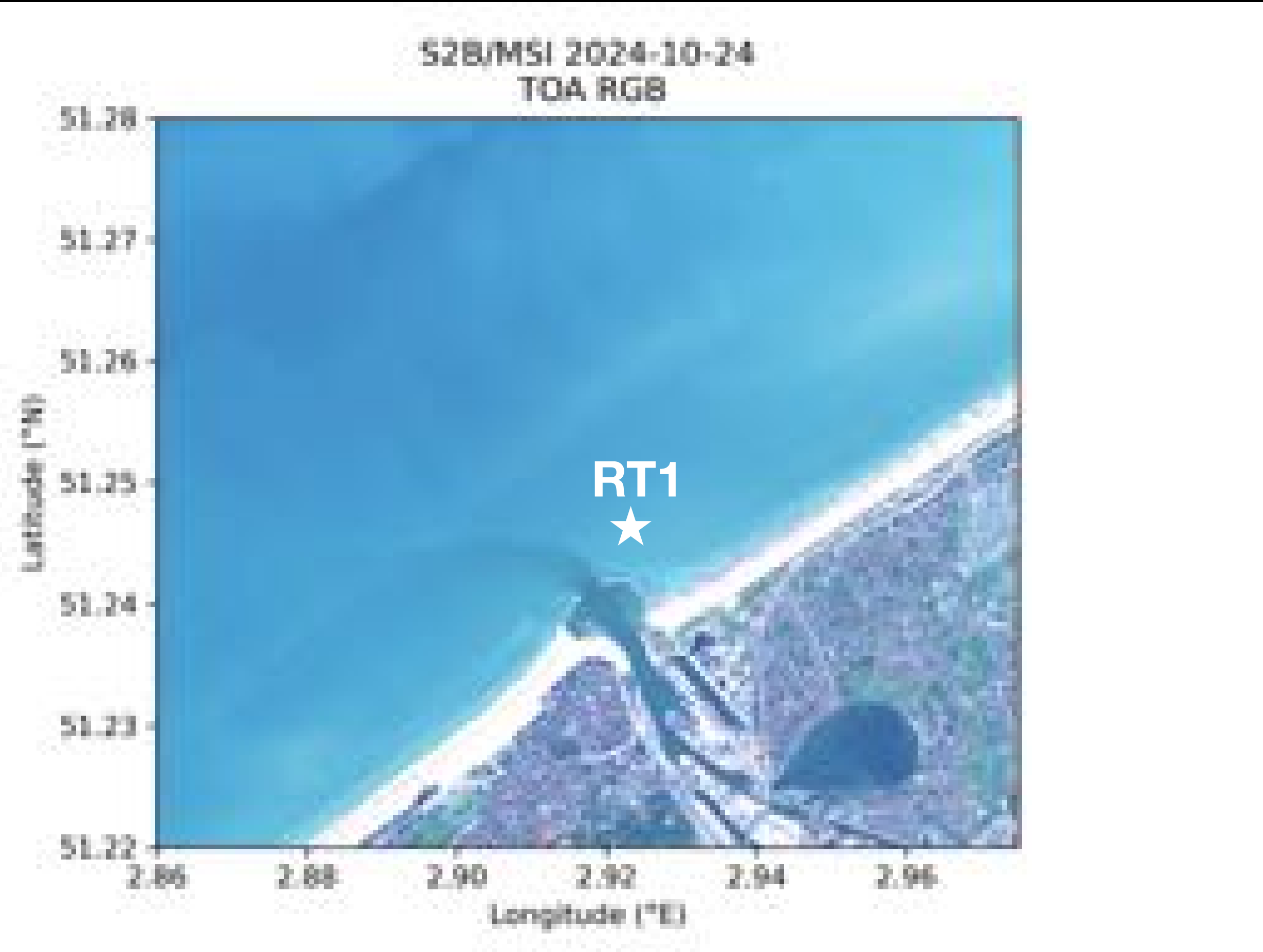
$$\frac{T_u^{dif}}{T_u^{tot}}$$

Modeled by RTM

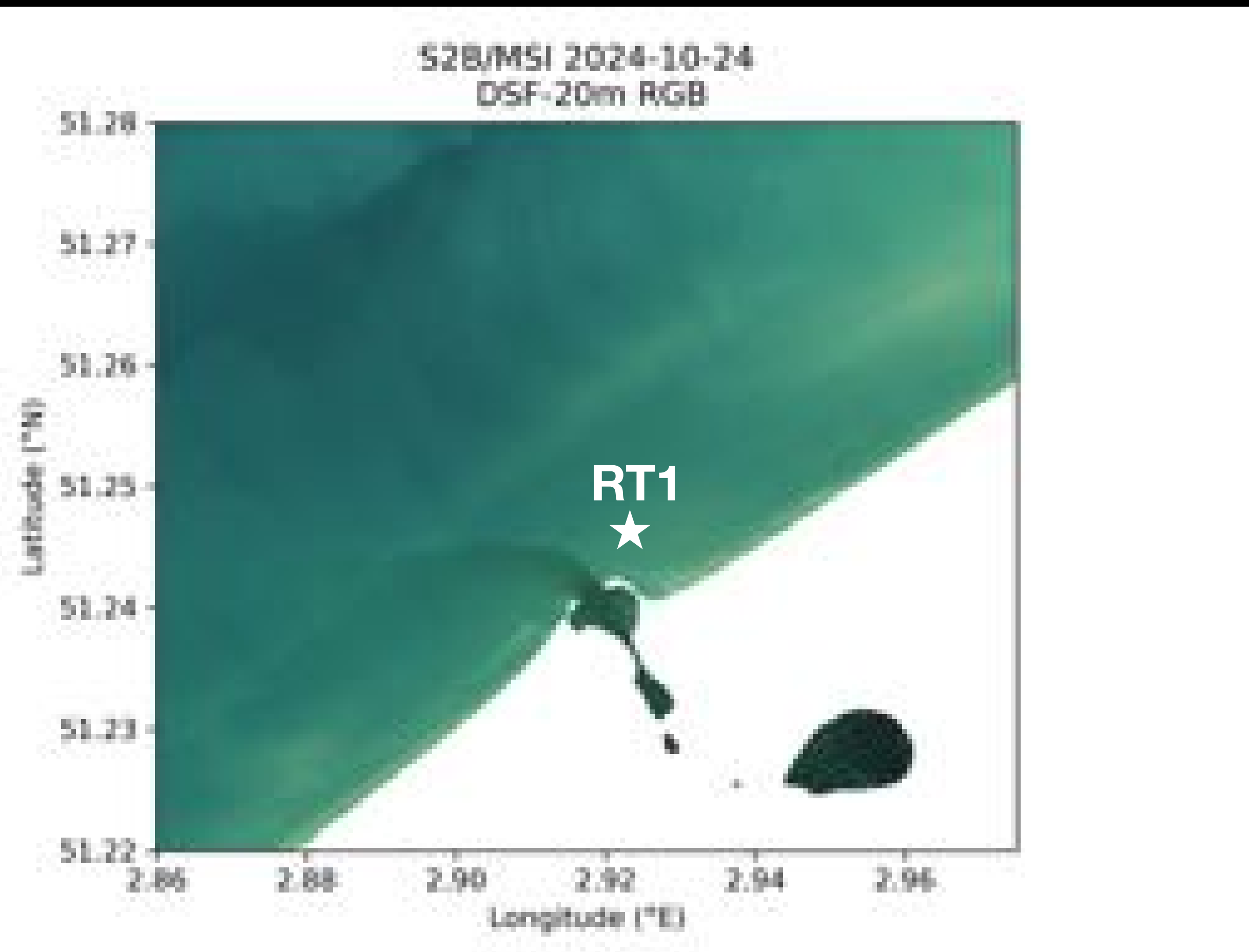
$$\frac{\rho_t - \rho_{path}}{\rho_t^{HYP} - \rho_{path}} = \frac{T_u^{dif}}{T_u^{tot}}$$

Estimated from
image using high τ_a

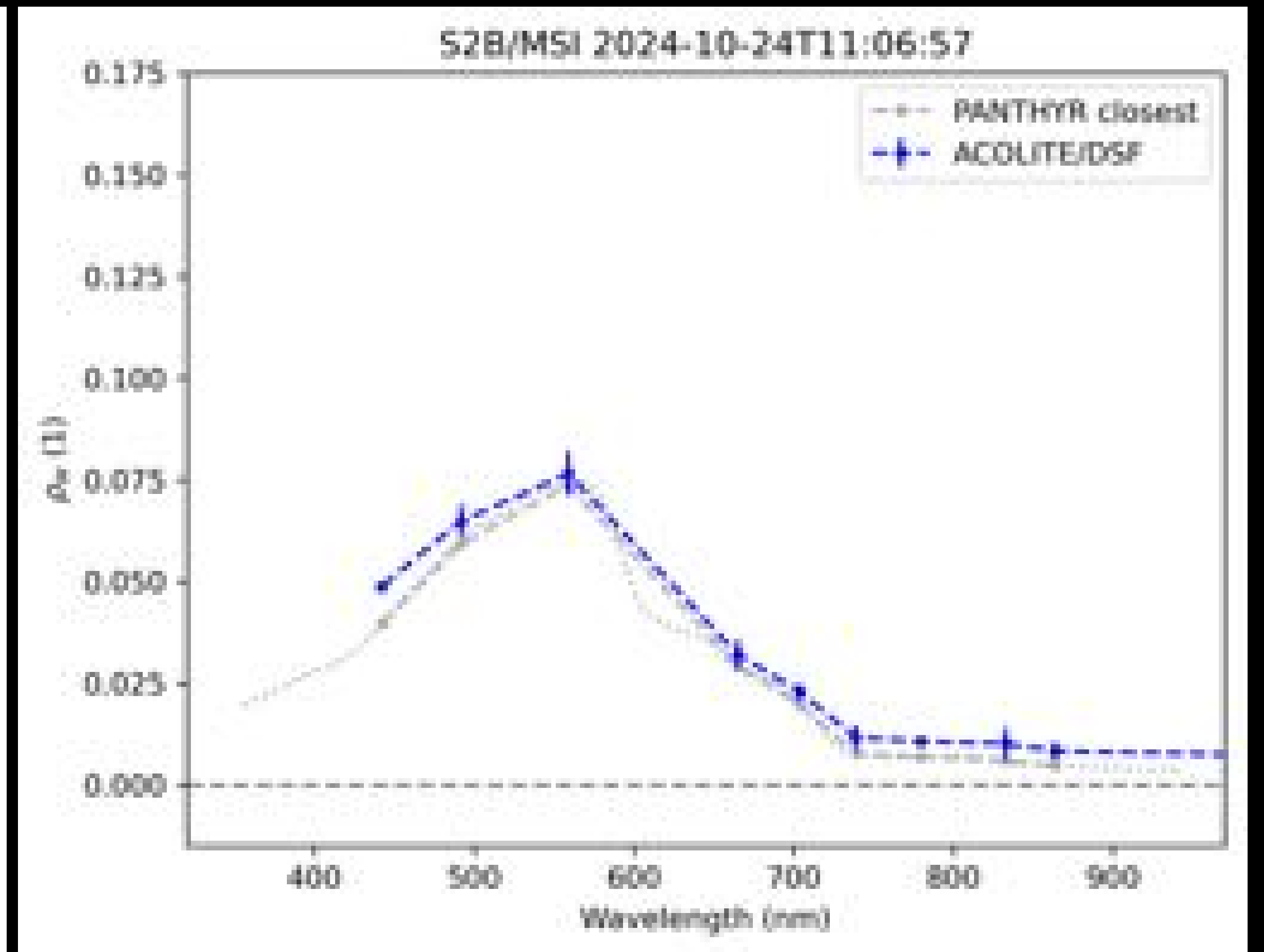
2024-10-24



DSF

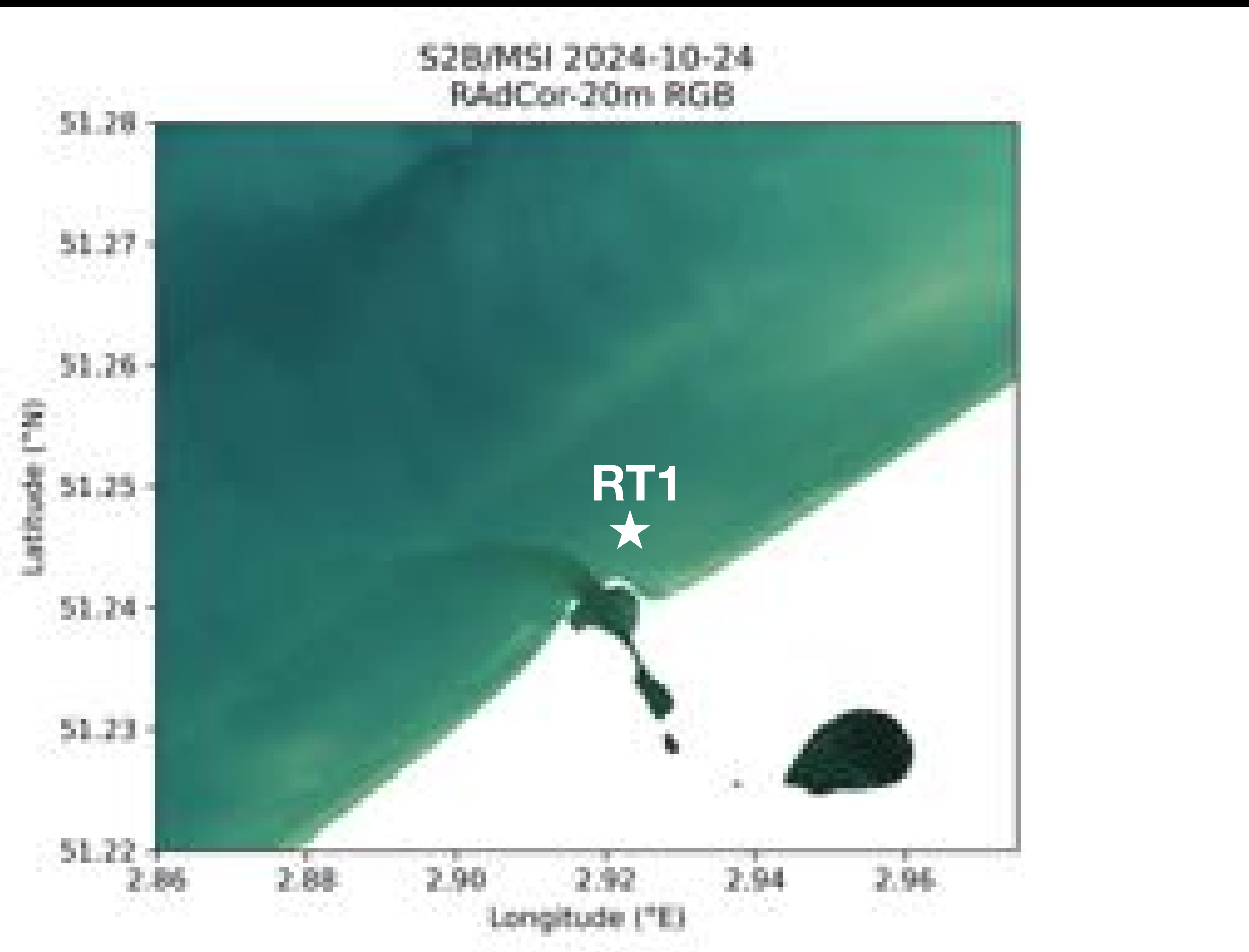


brighter reflectance, less pronounced green

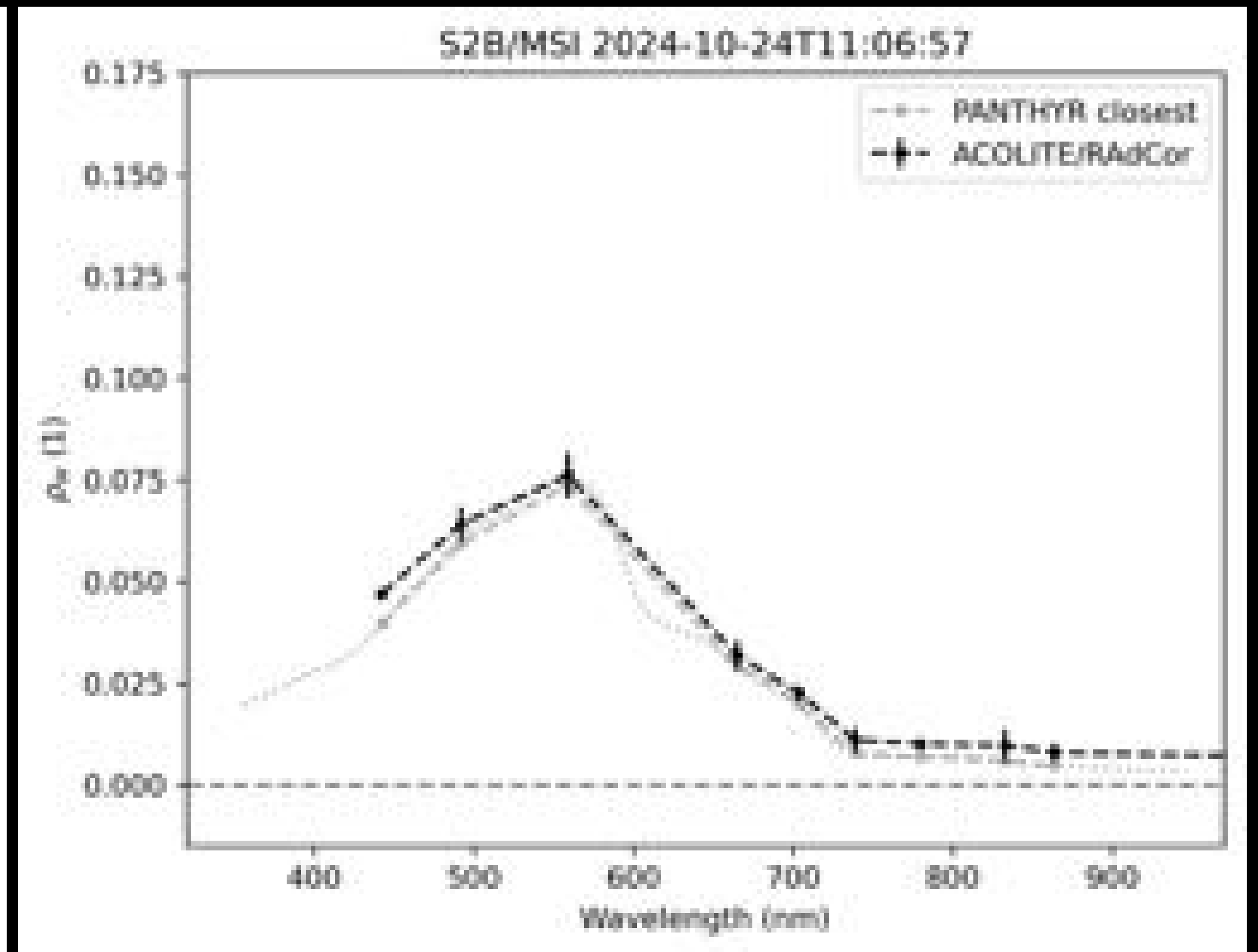


undercorrection, slightly higher in Blue and NIR

RAdCor

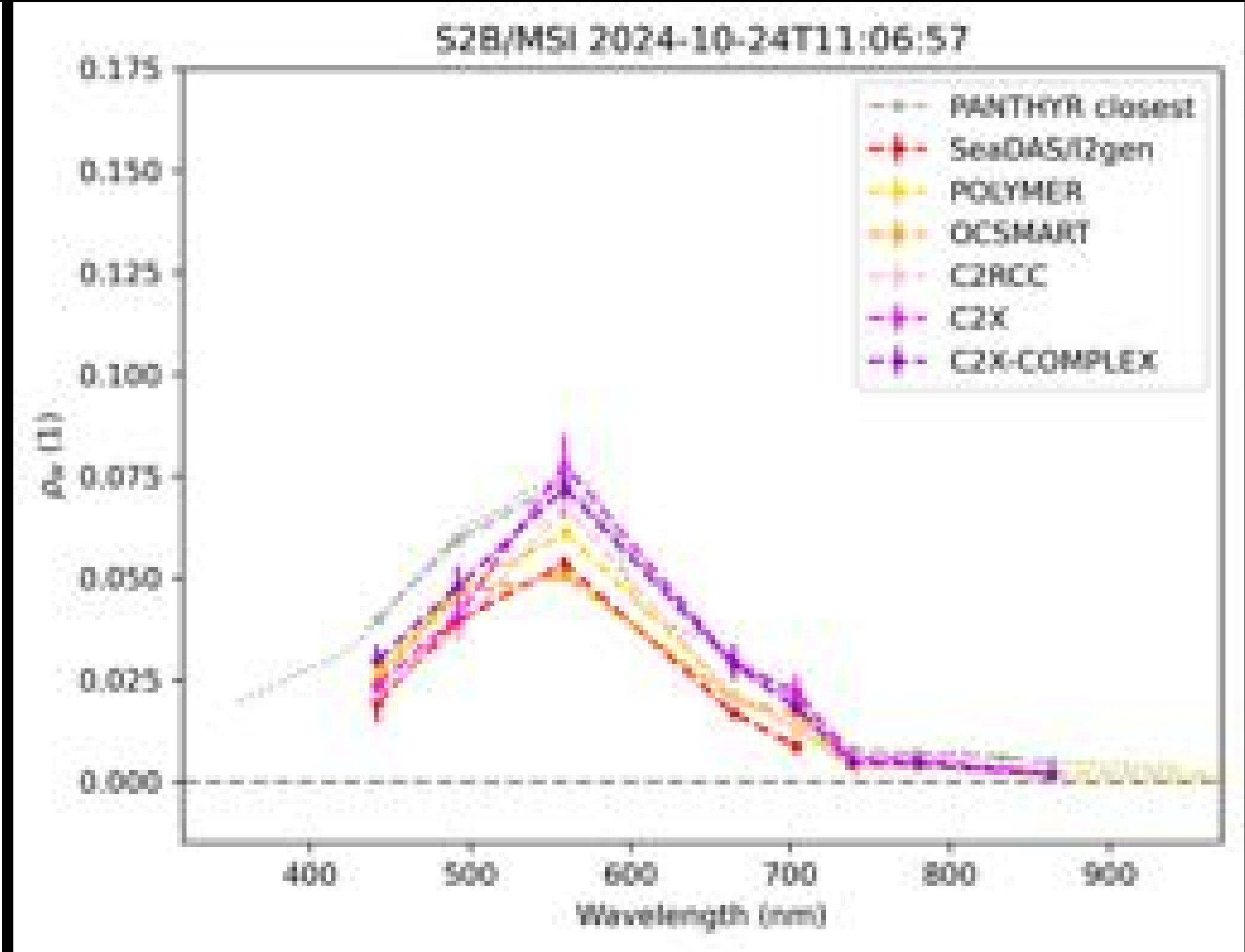
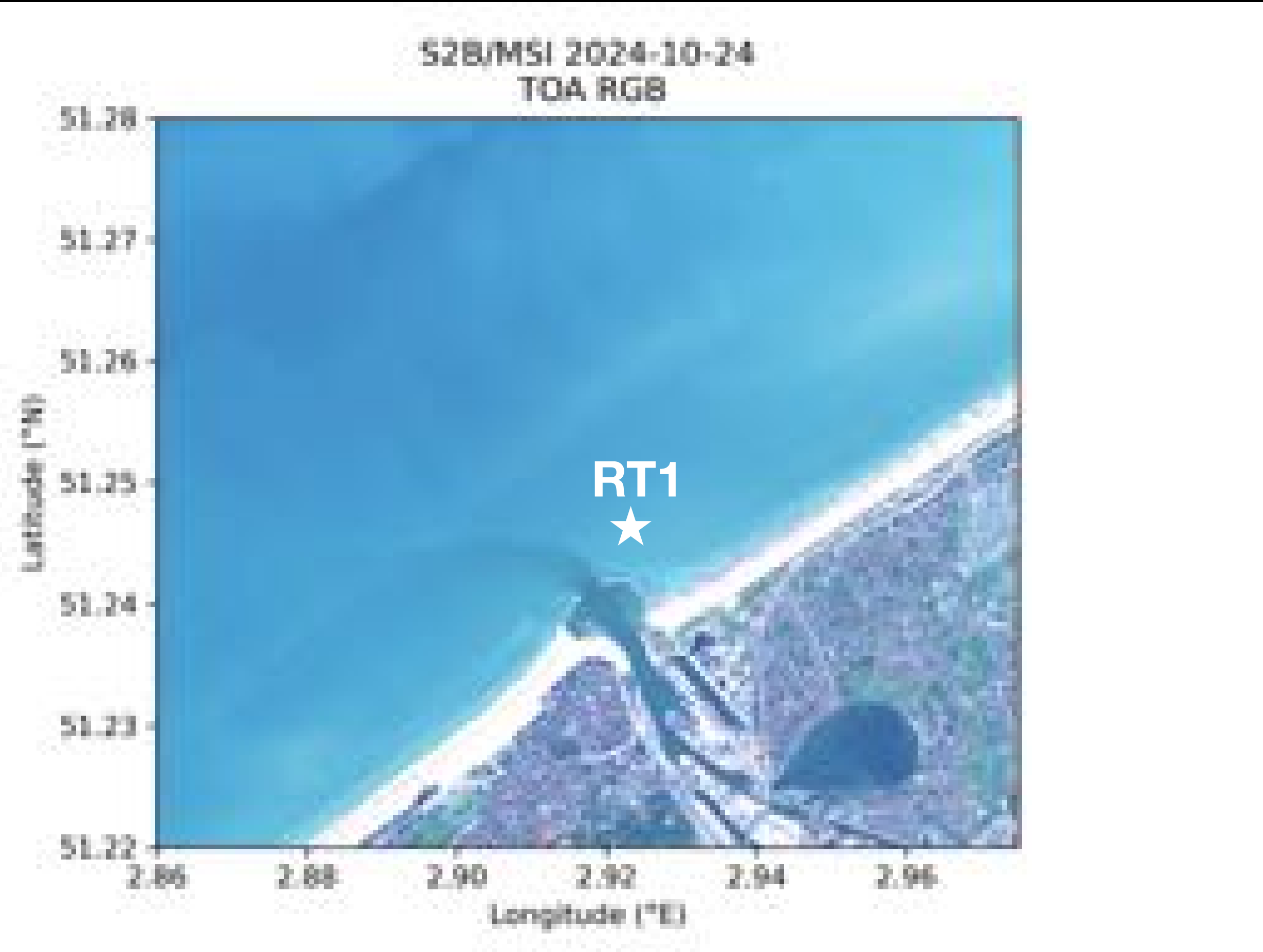


very similar to DSF, lower reflectance in port and lake,
slightly sharper appearance

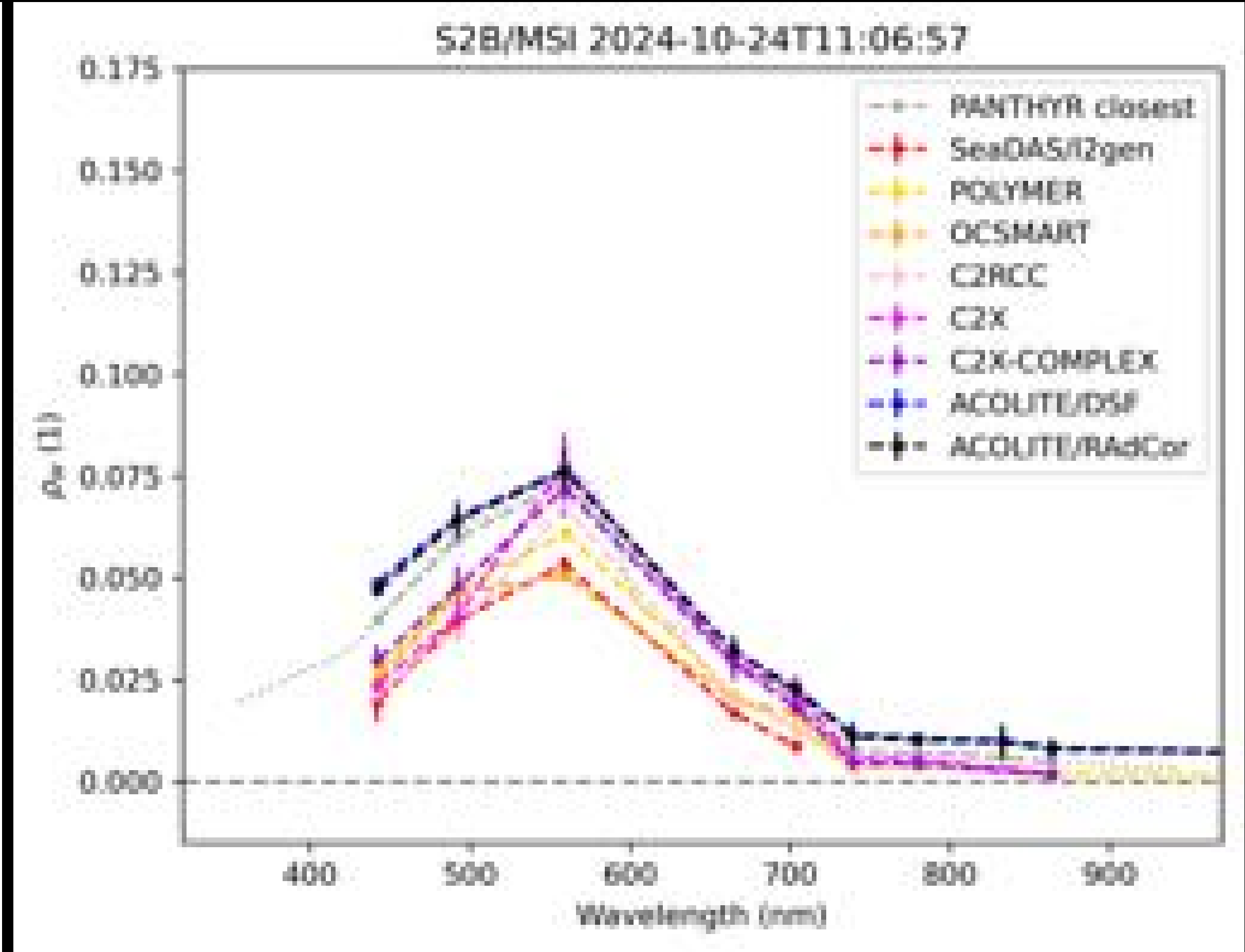
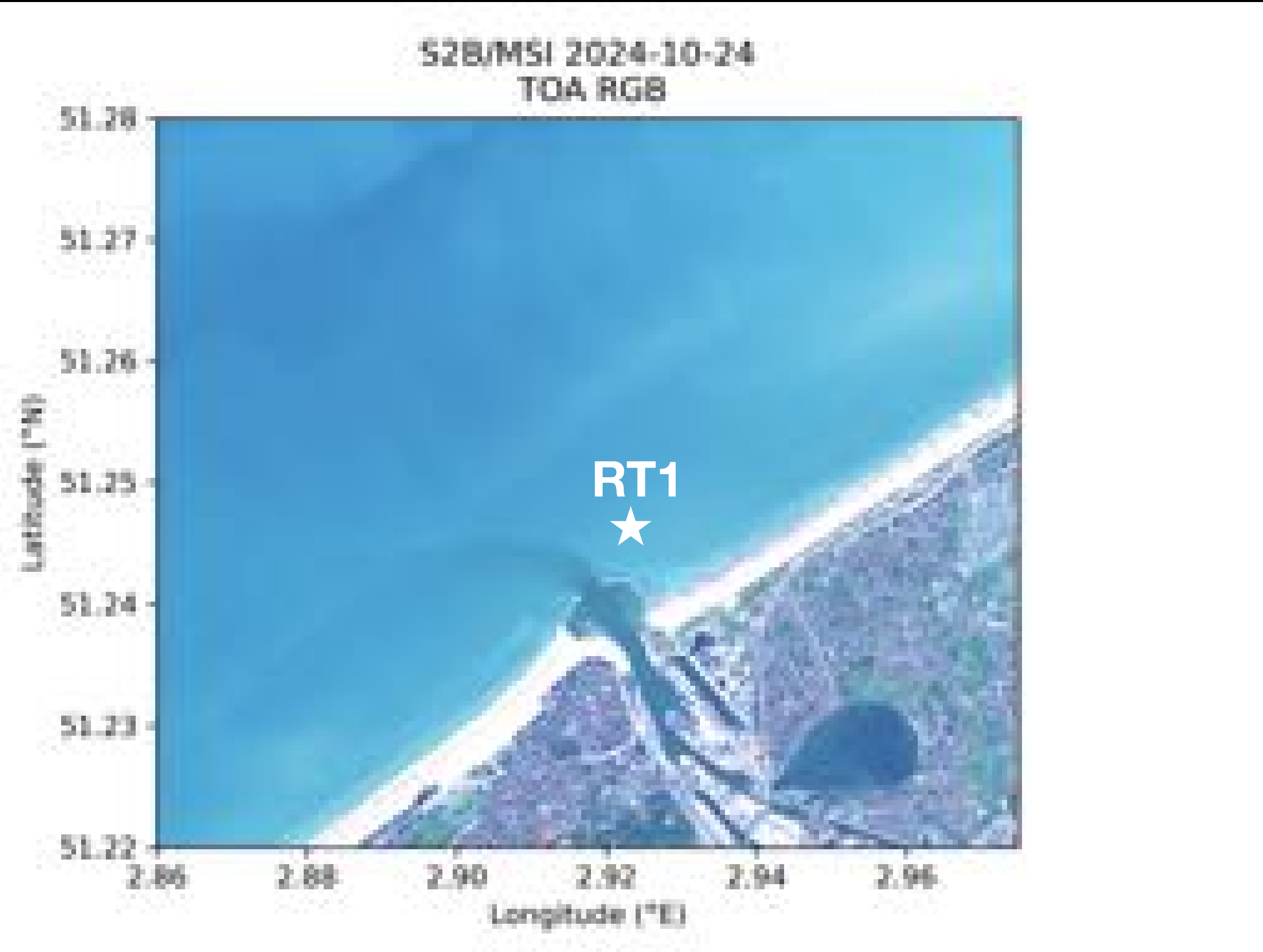


undercorrection, slight improvement to spectral shape
compared to DSF

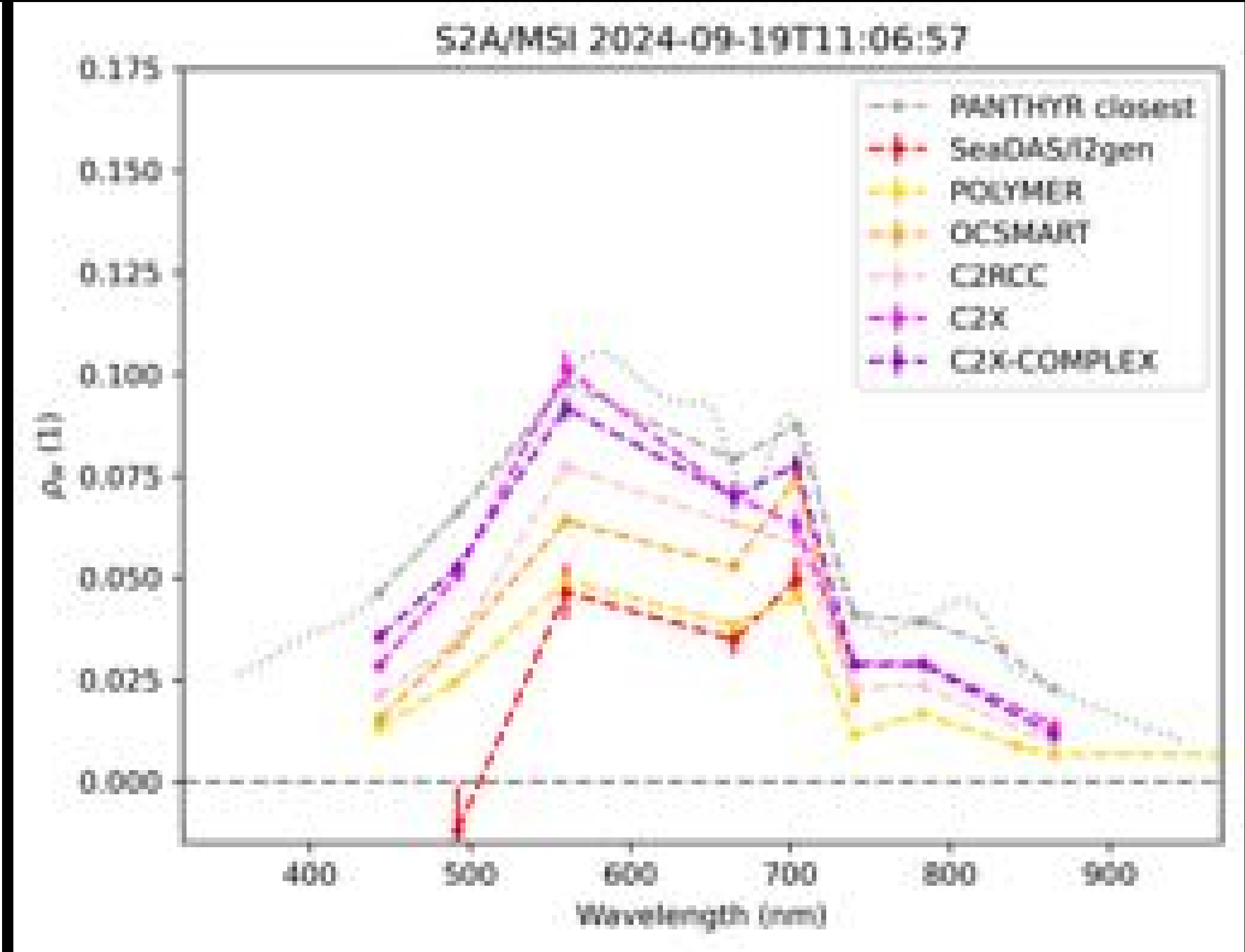
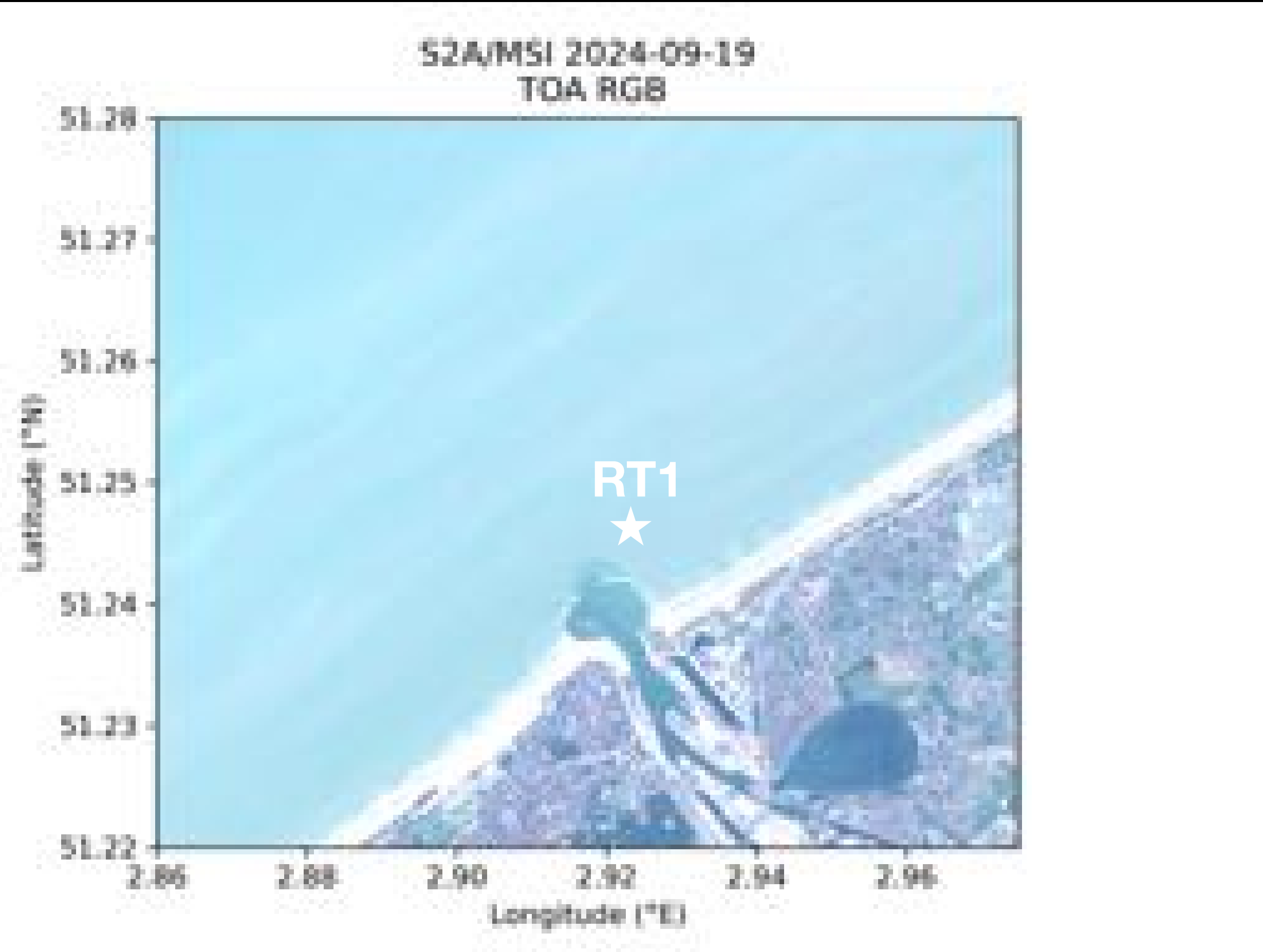
2024-10-24



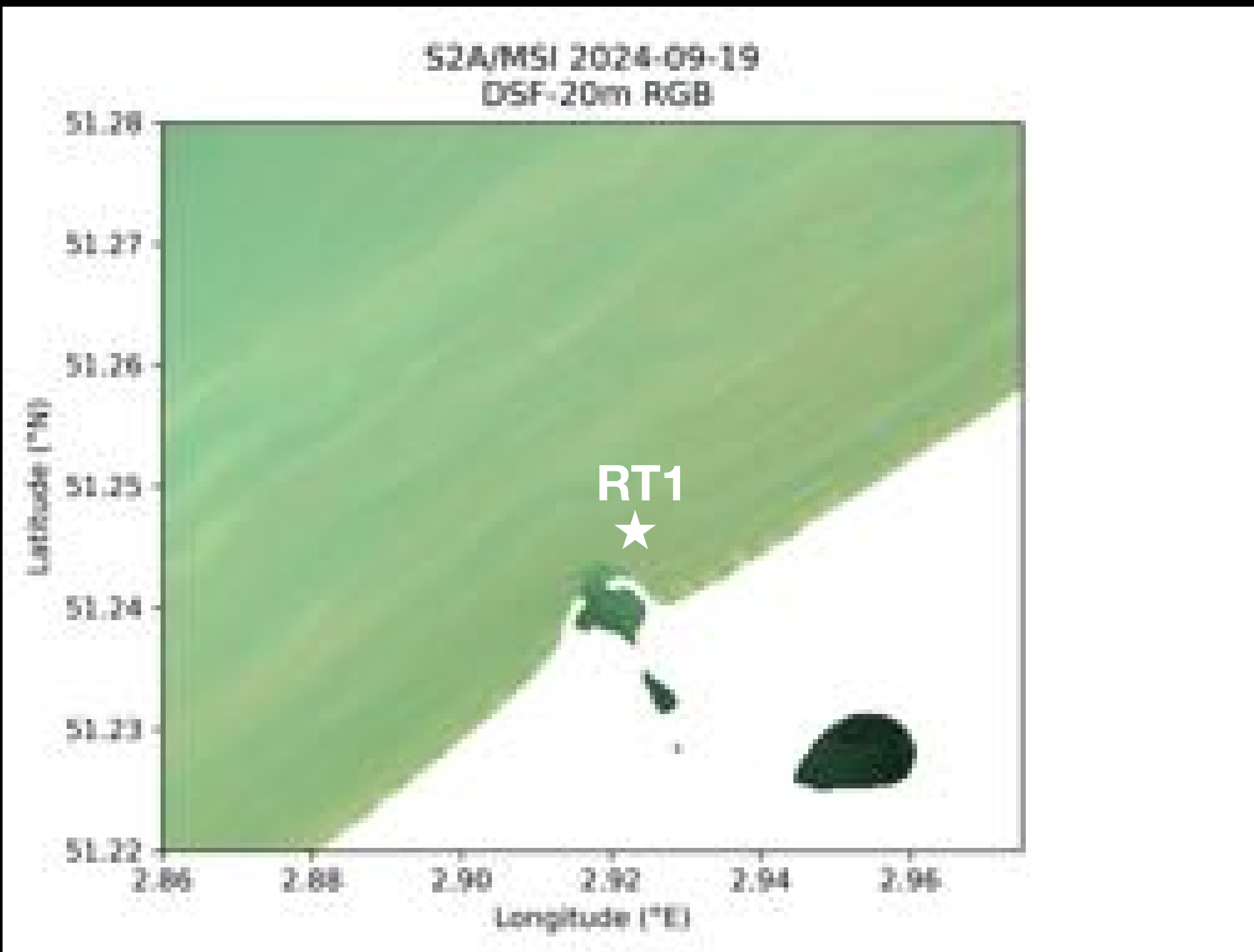
2024-10-24



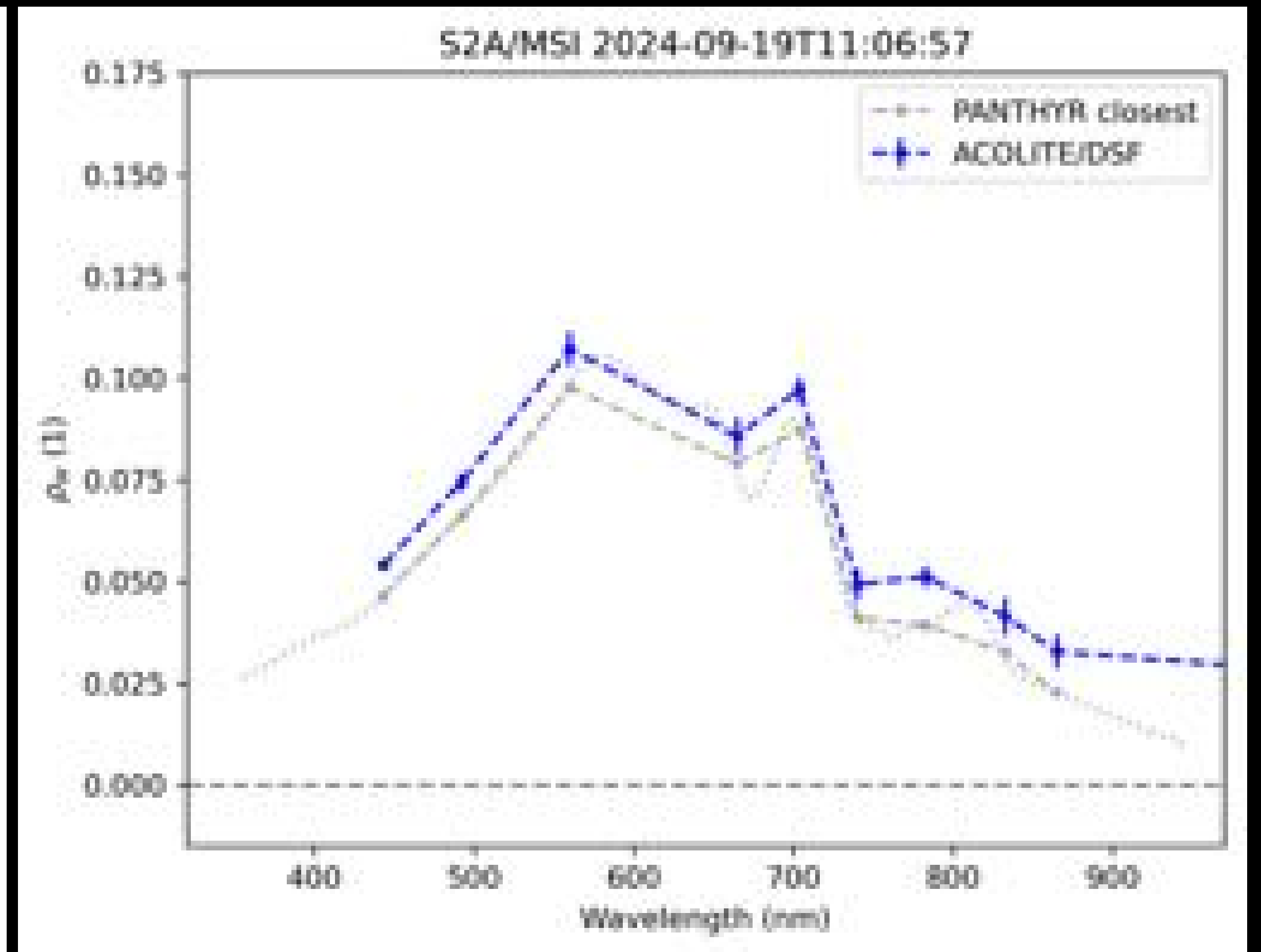
2024-09-19



DSF

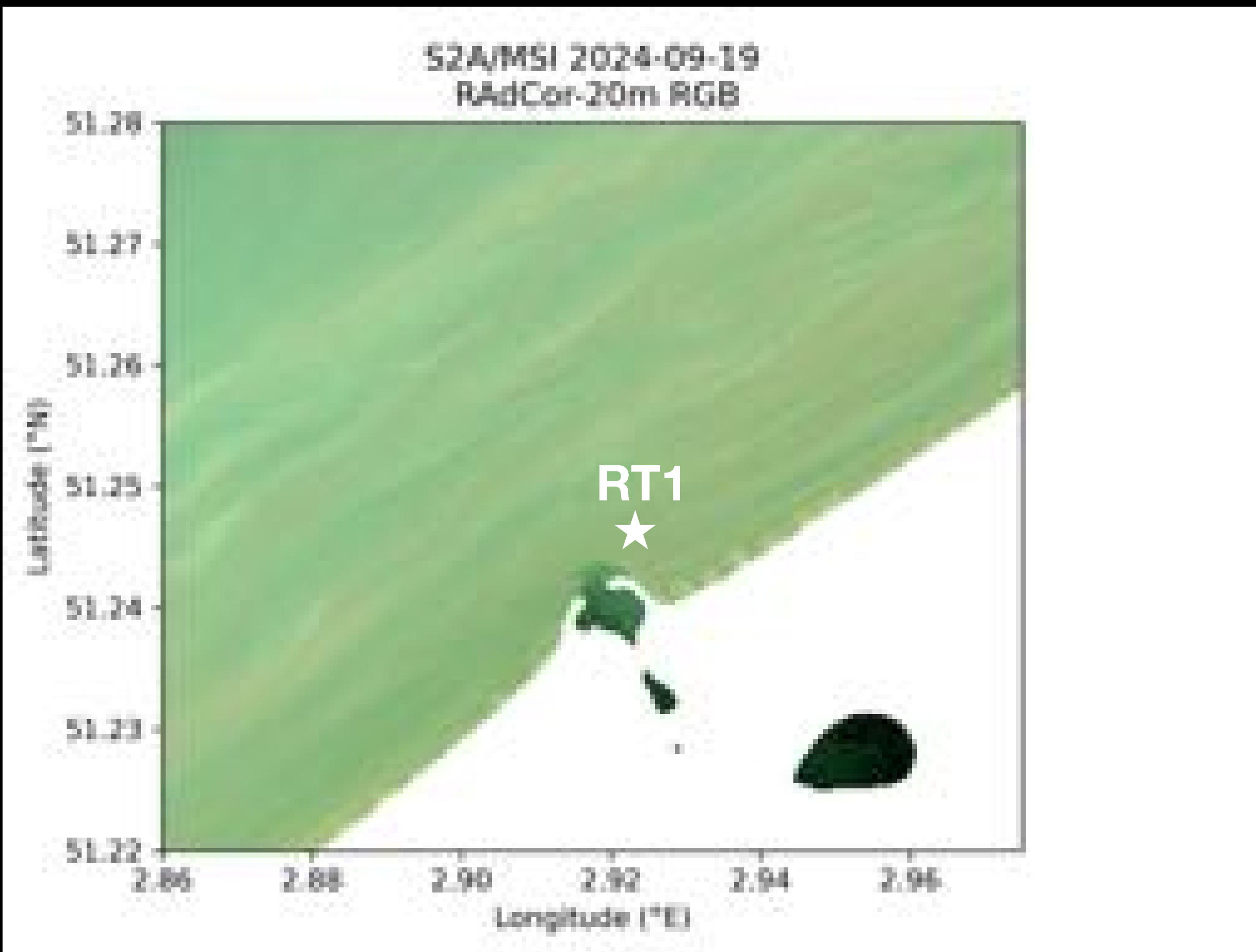


brighter reflectance, more grey/white coloured

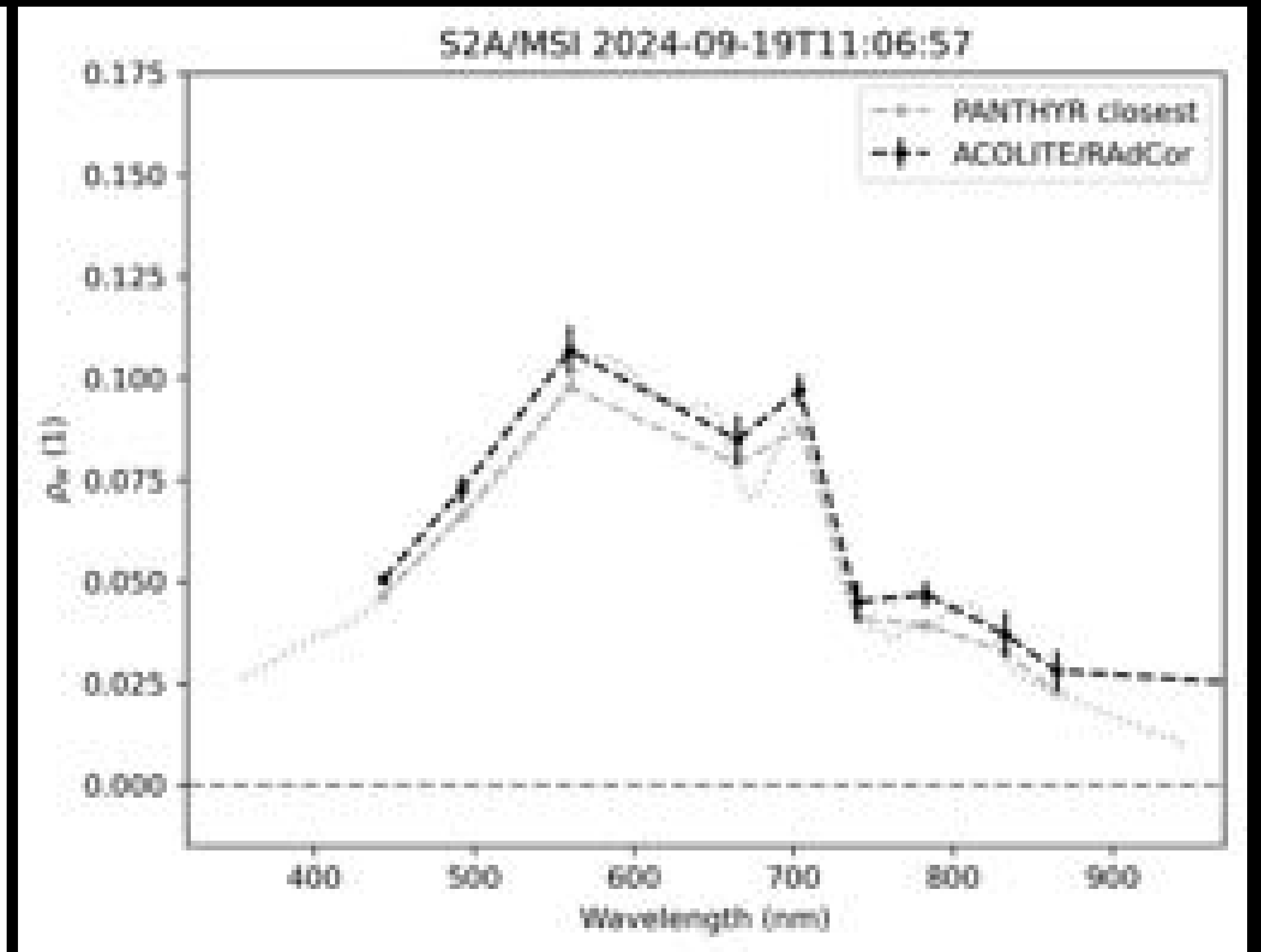


undercorrection, rather good spectral shape

RAdCor

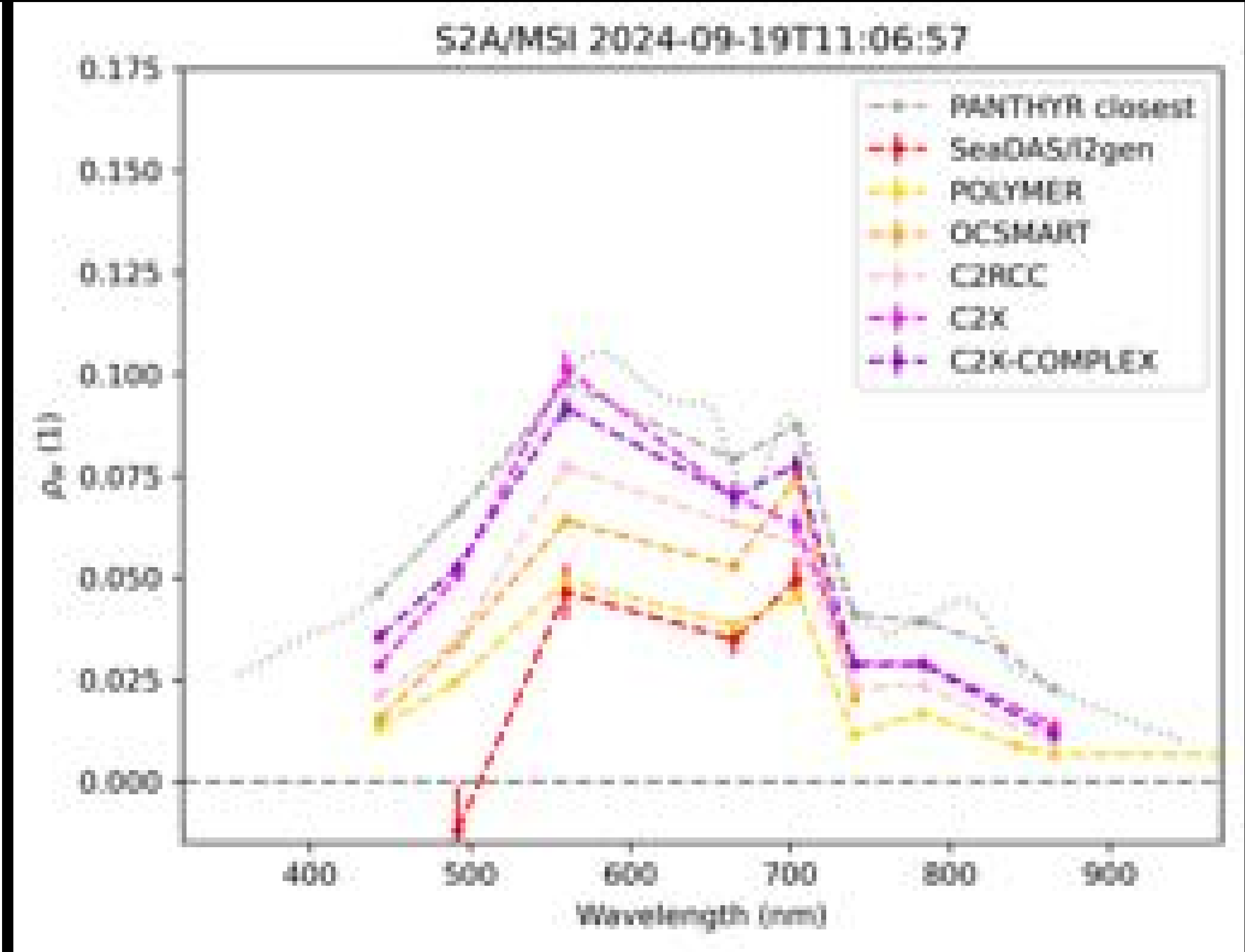
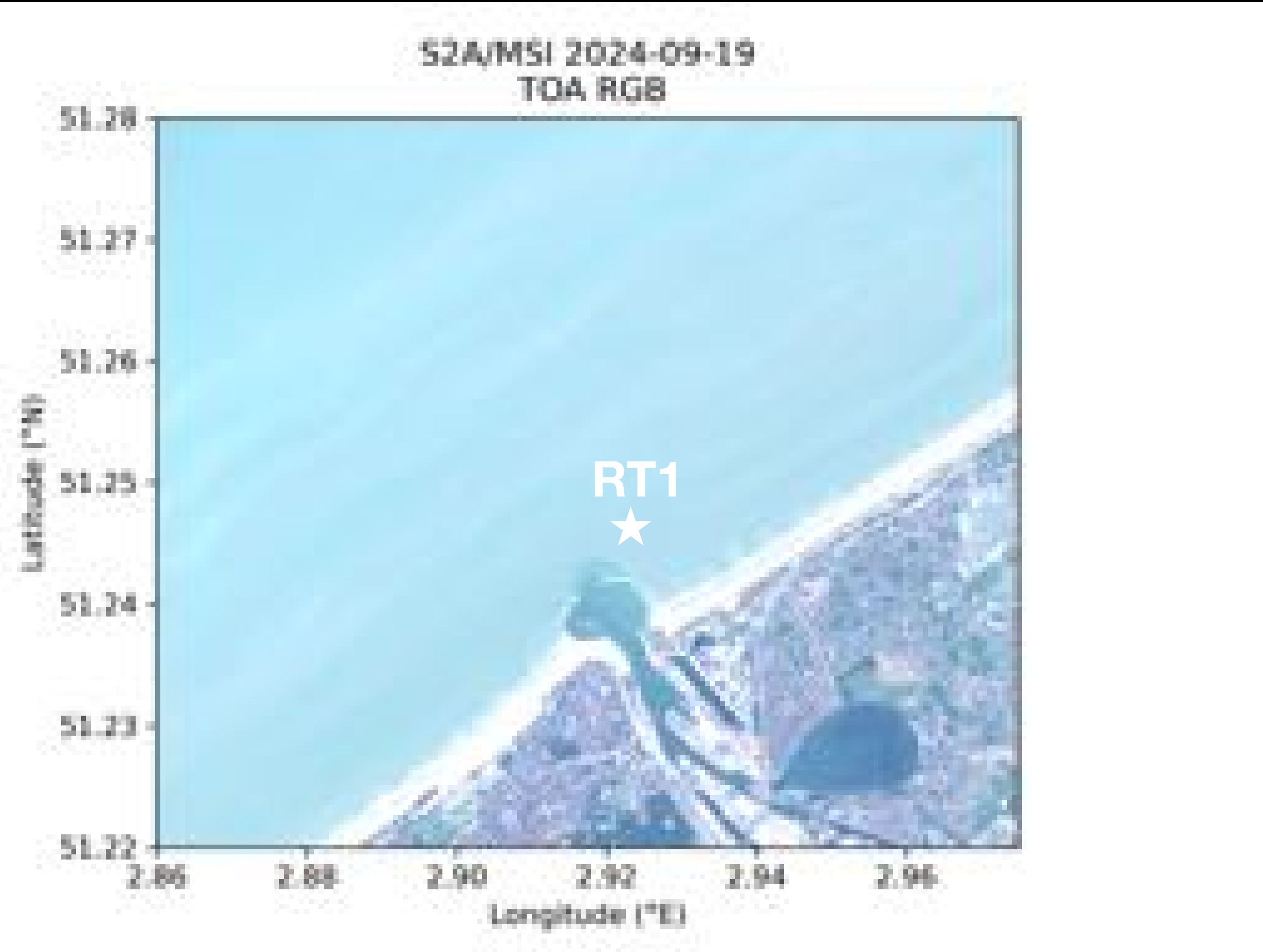


very similar to DSF, lower reflectance in port and lake,
slightly sharper appearance

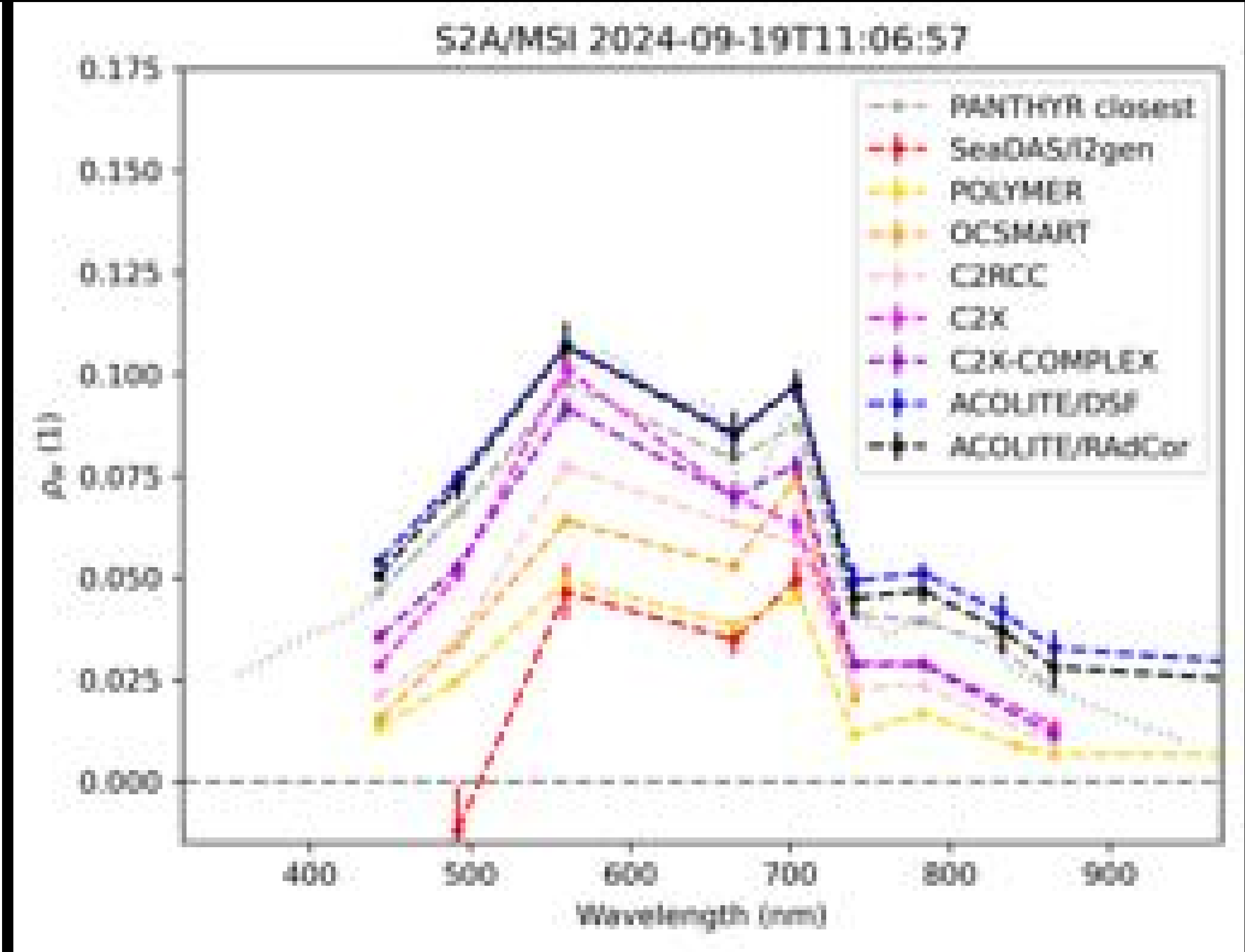
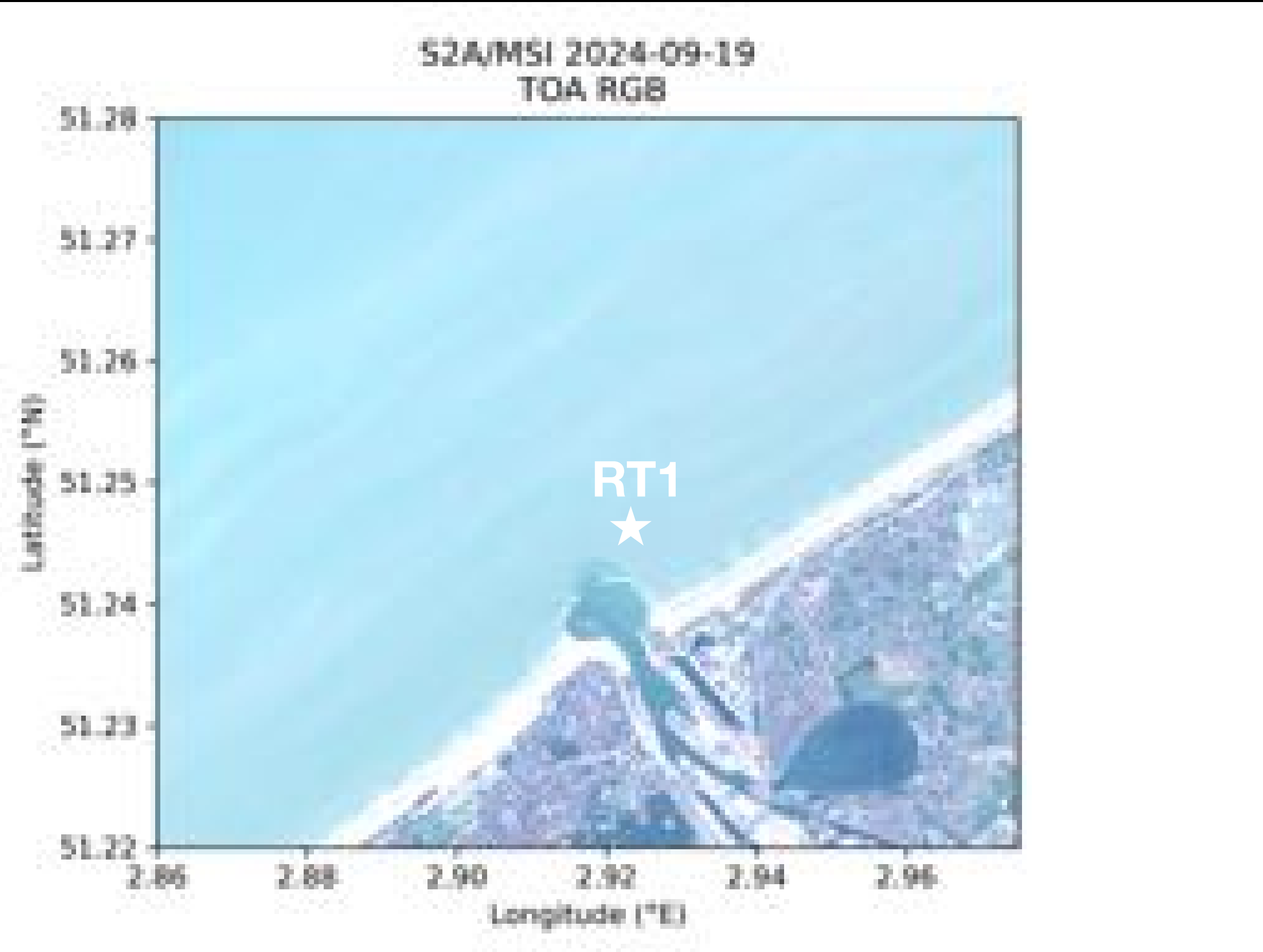


undercorrection, slight improvement to spectral shape
compared to DSF

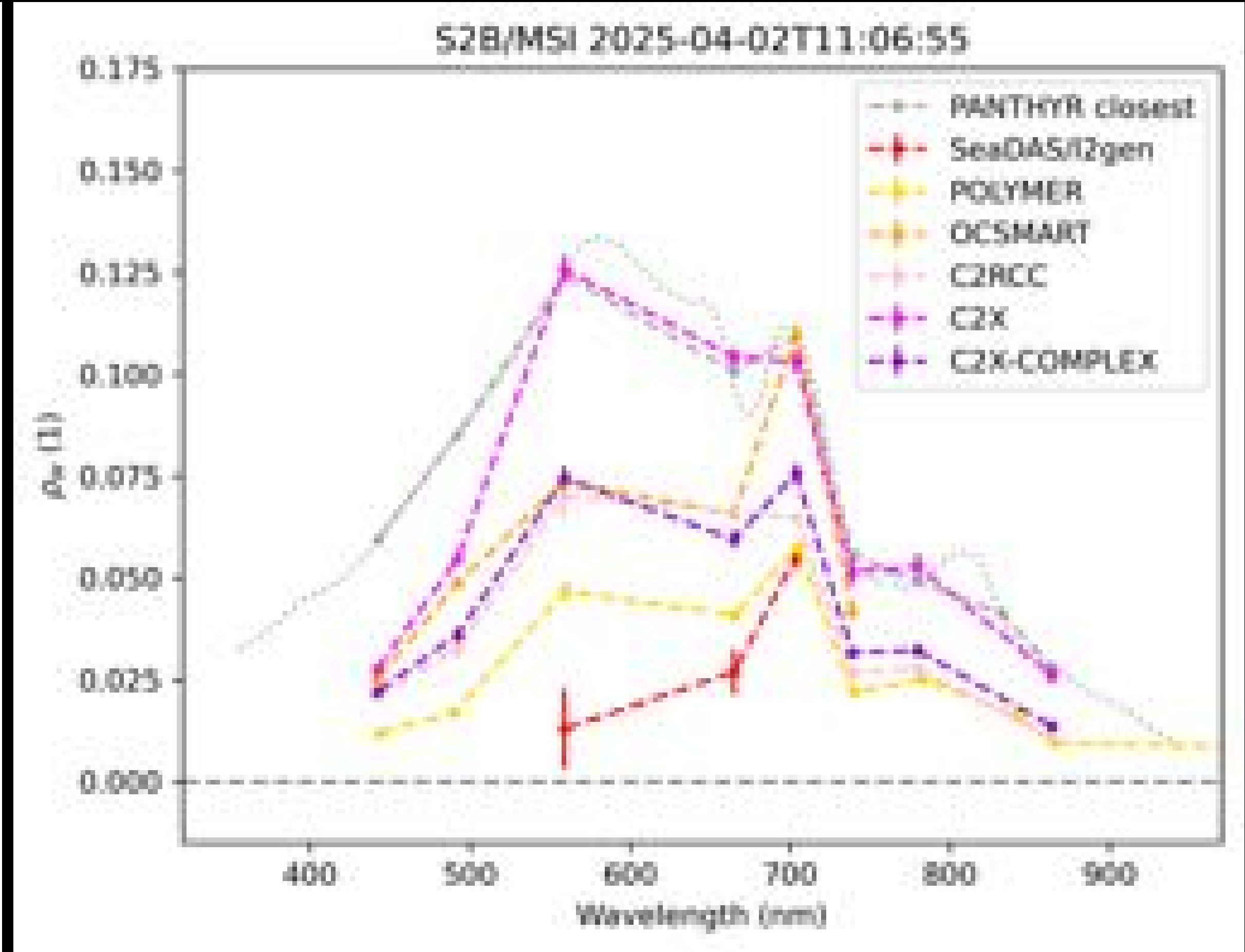
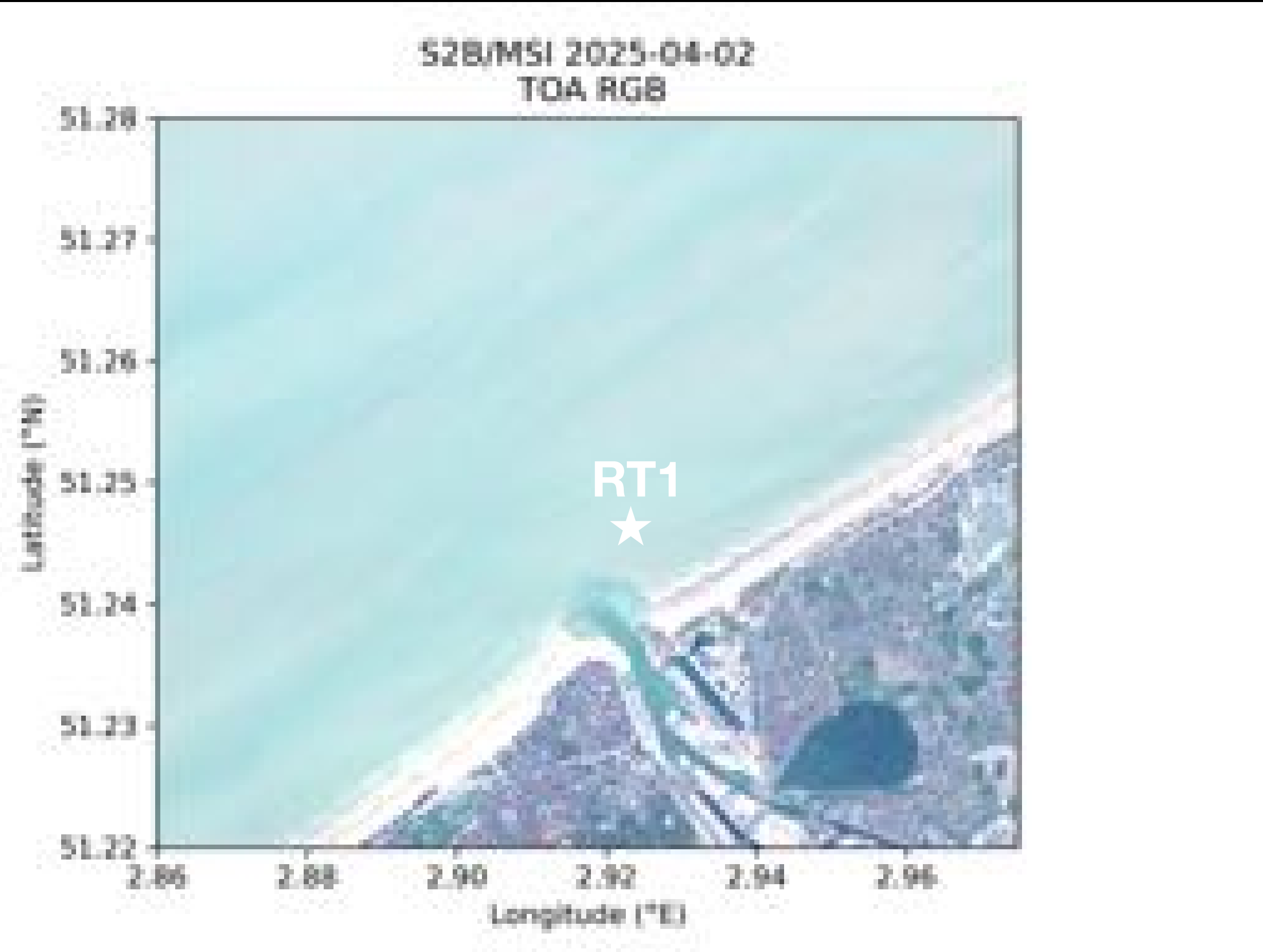
2024-09-19



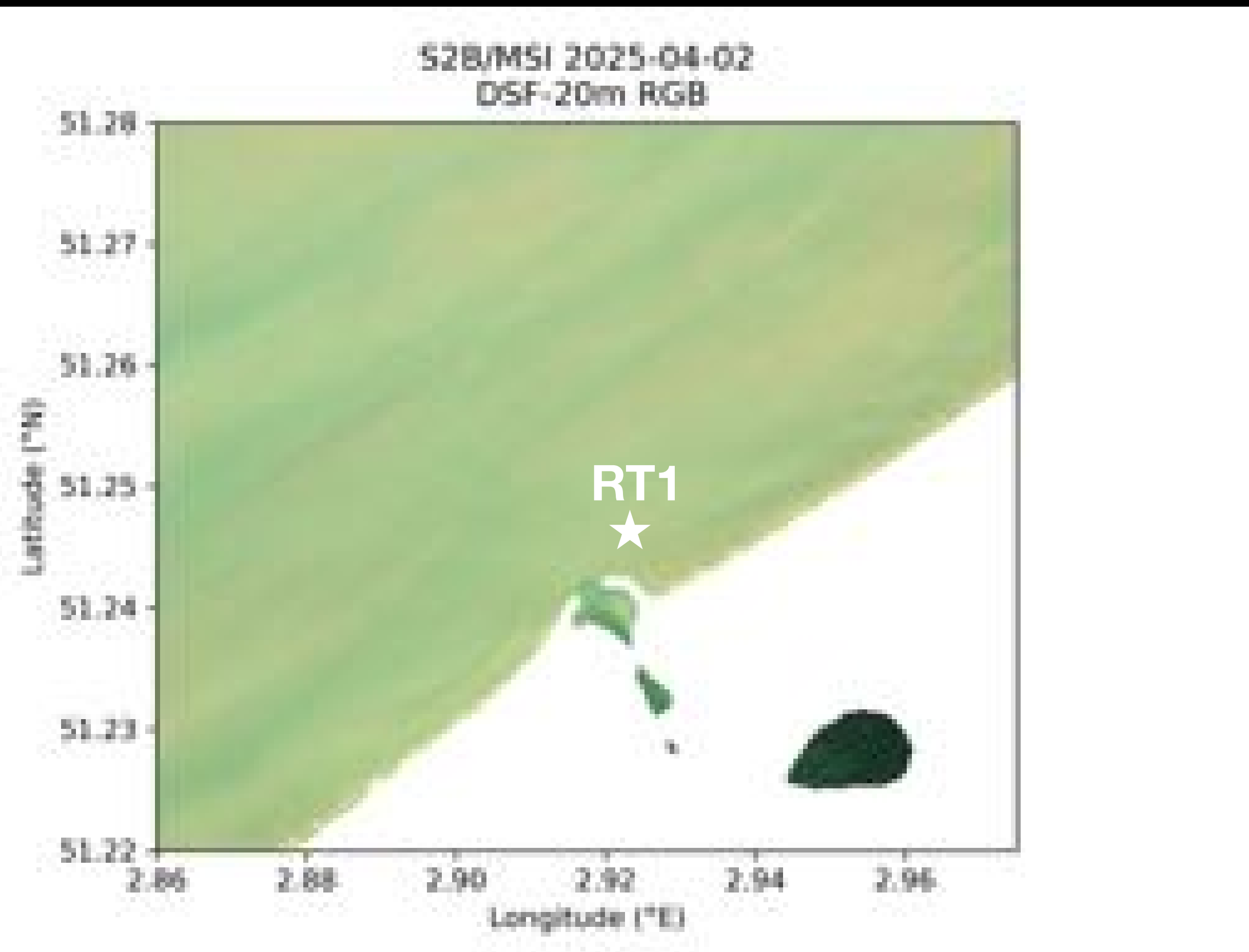
2024-09-19



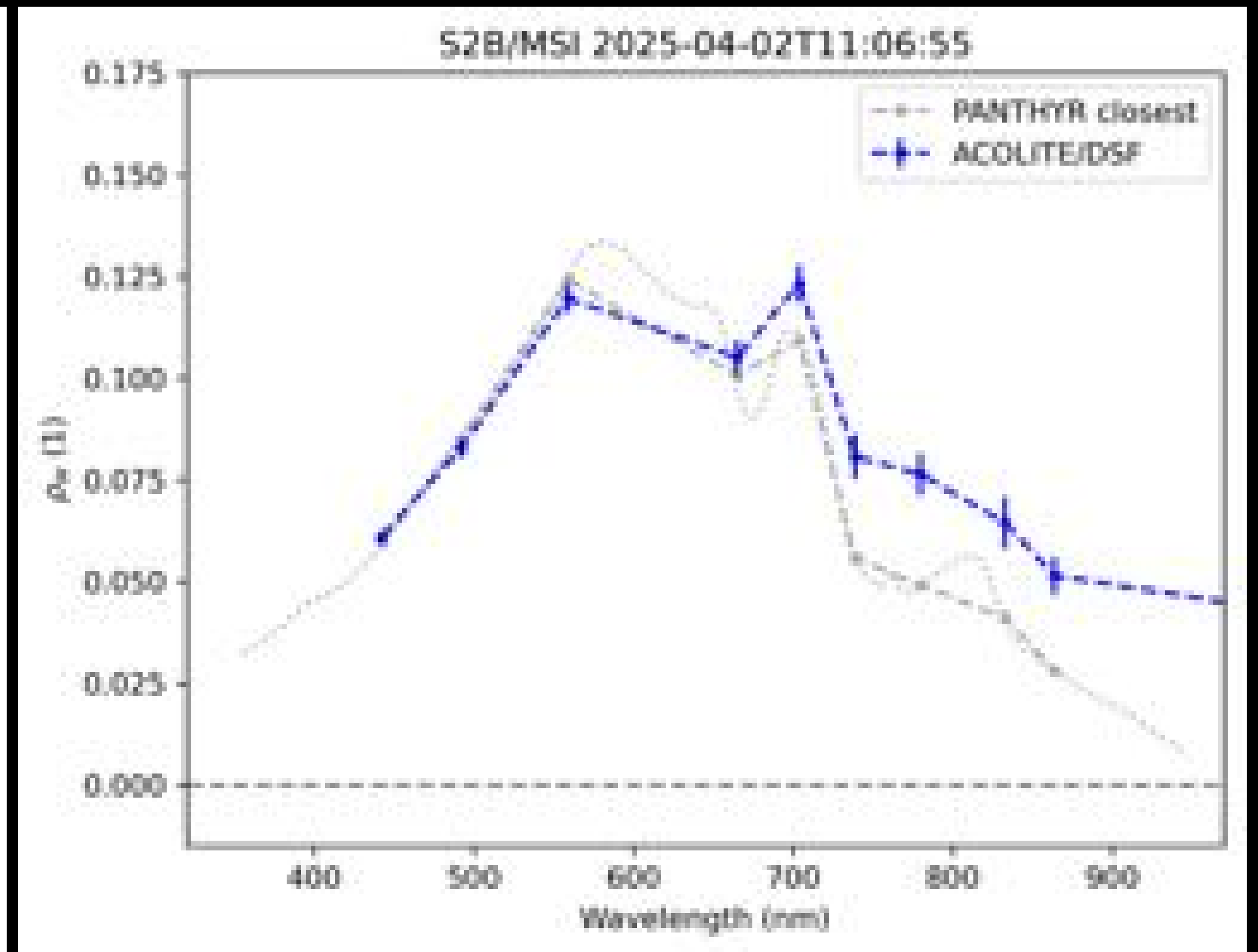
2025-04-02



DSF

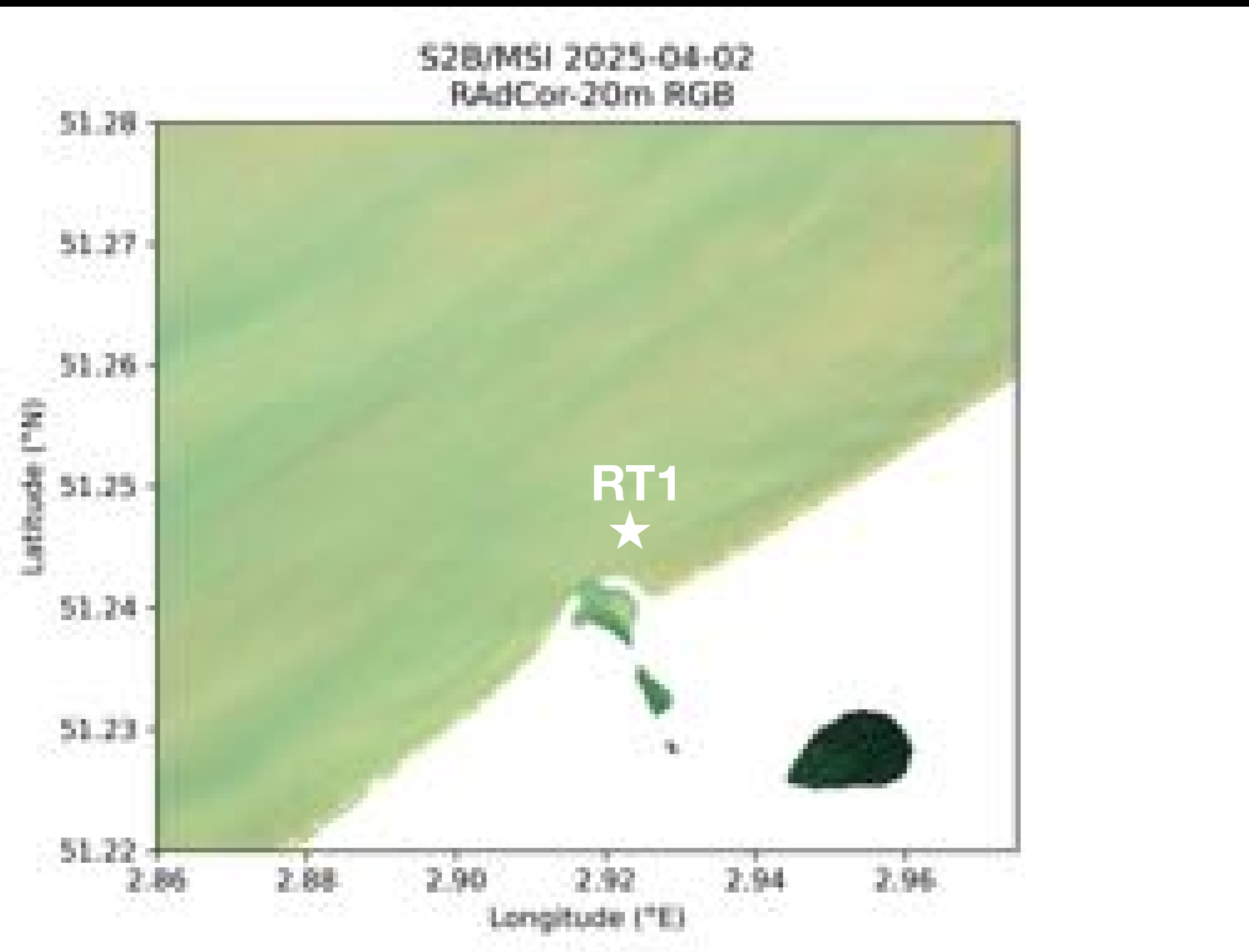


brighter reflectance, more grey/white coloured

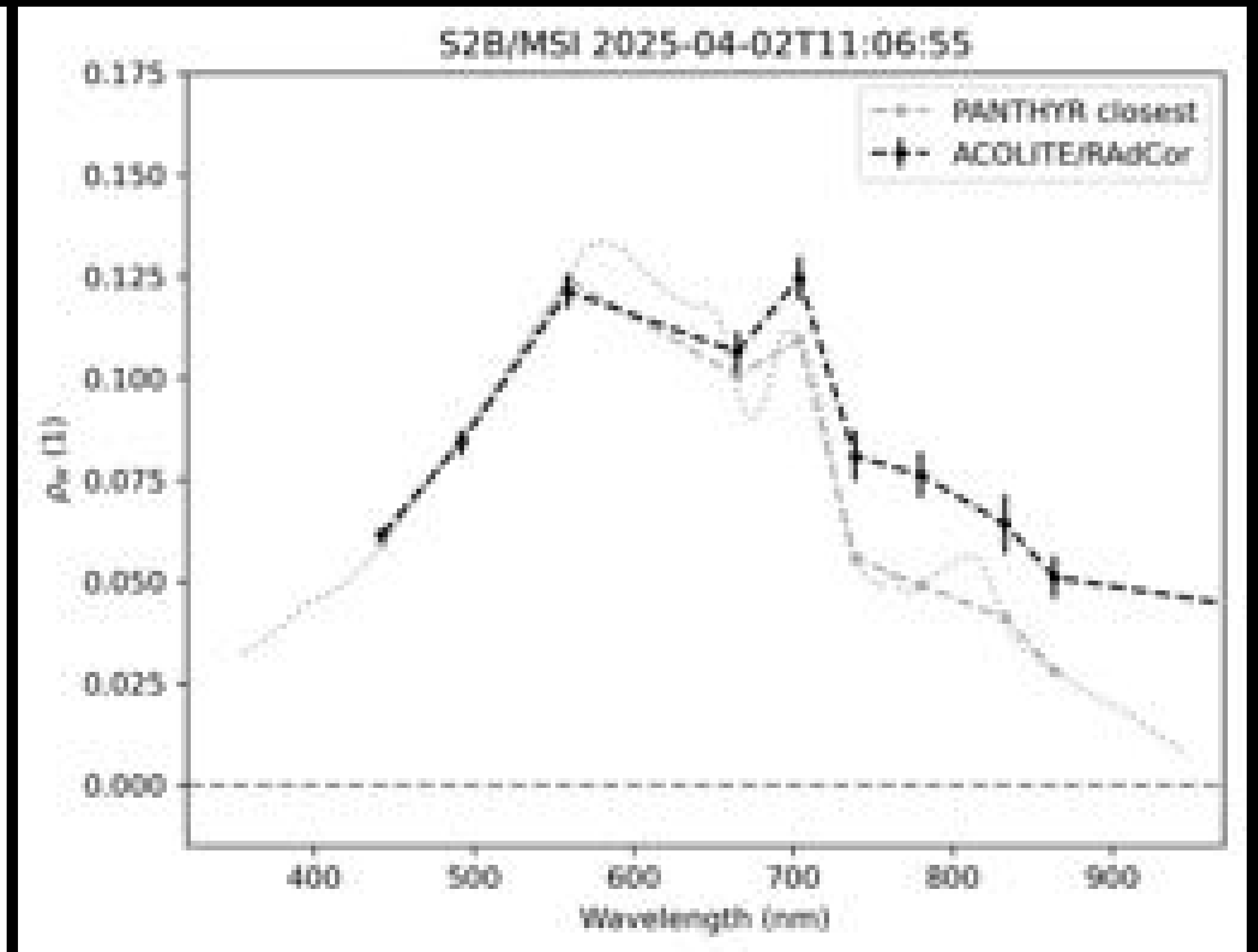


good match in VIS, rather good spectral shape, under-correction in NIR

RAdCor

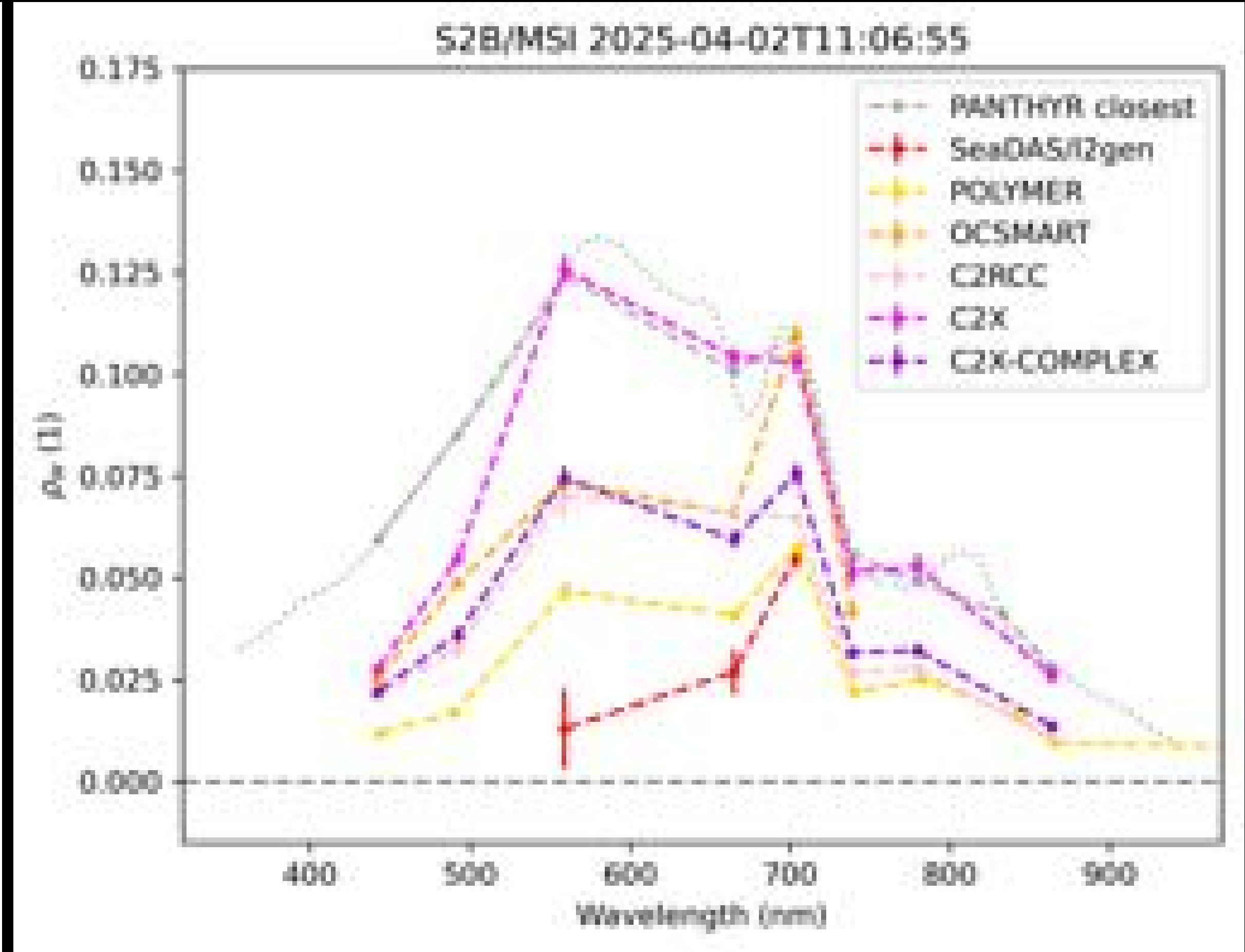
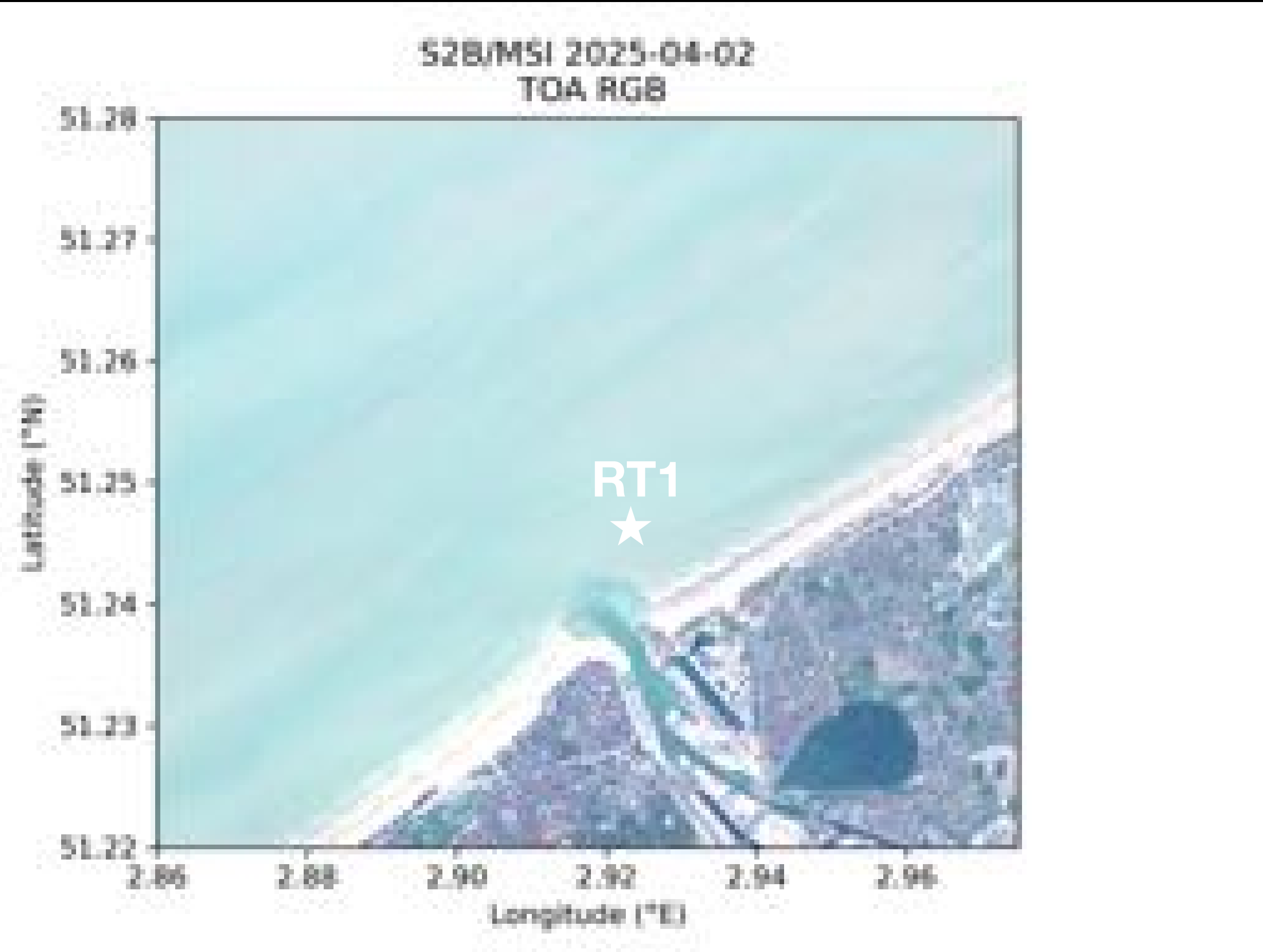


very similar to DSF, lower reflectance in port and lake,
slightly sharper appearance

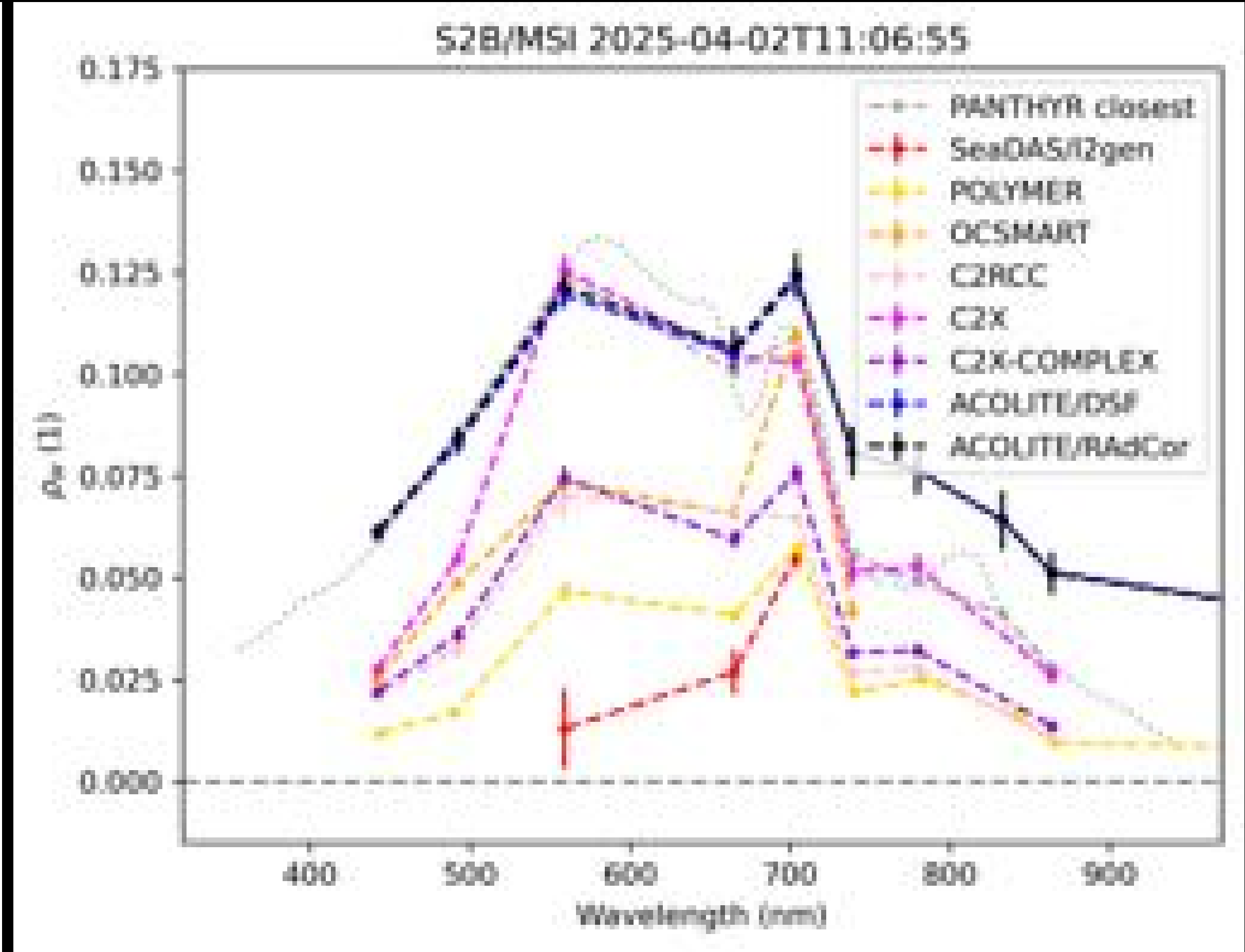
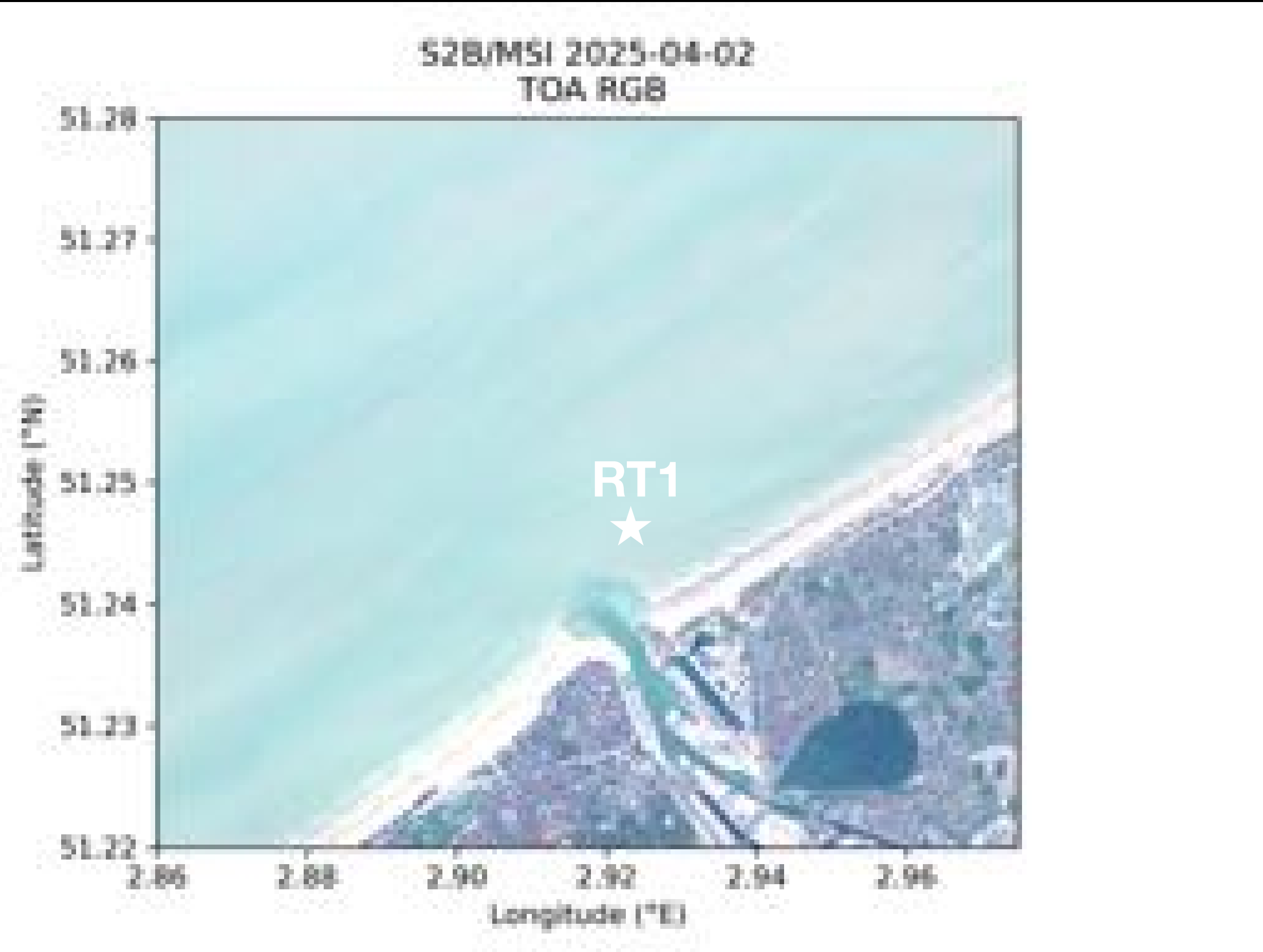


see DSF, still too high in NIR

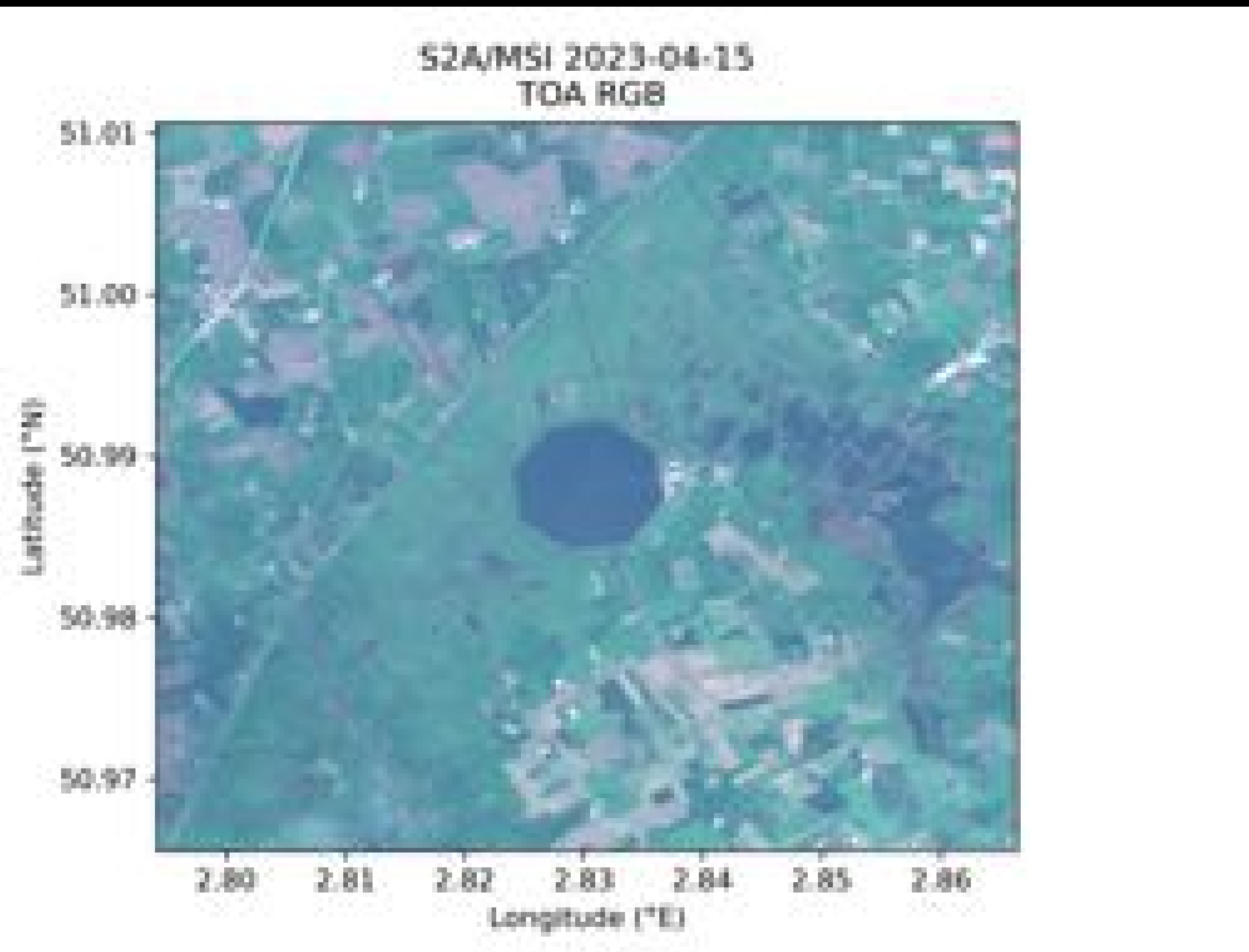
2025-04-02



2025-04-02



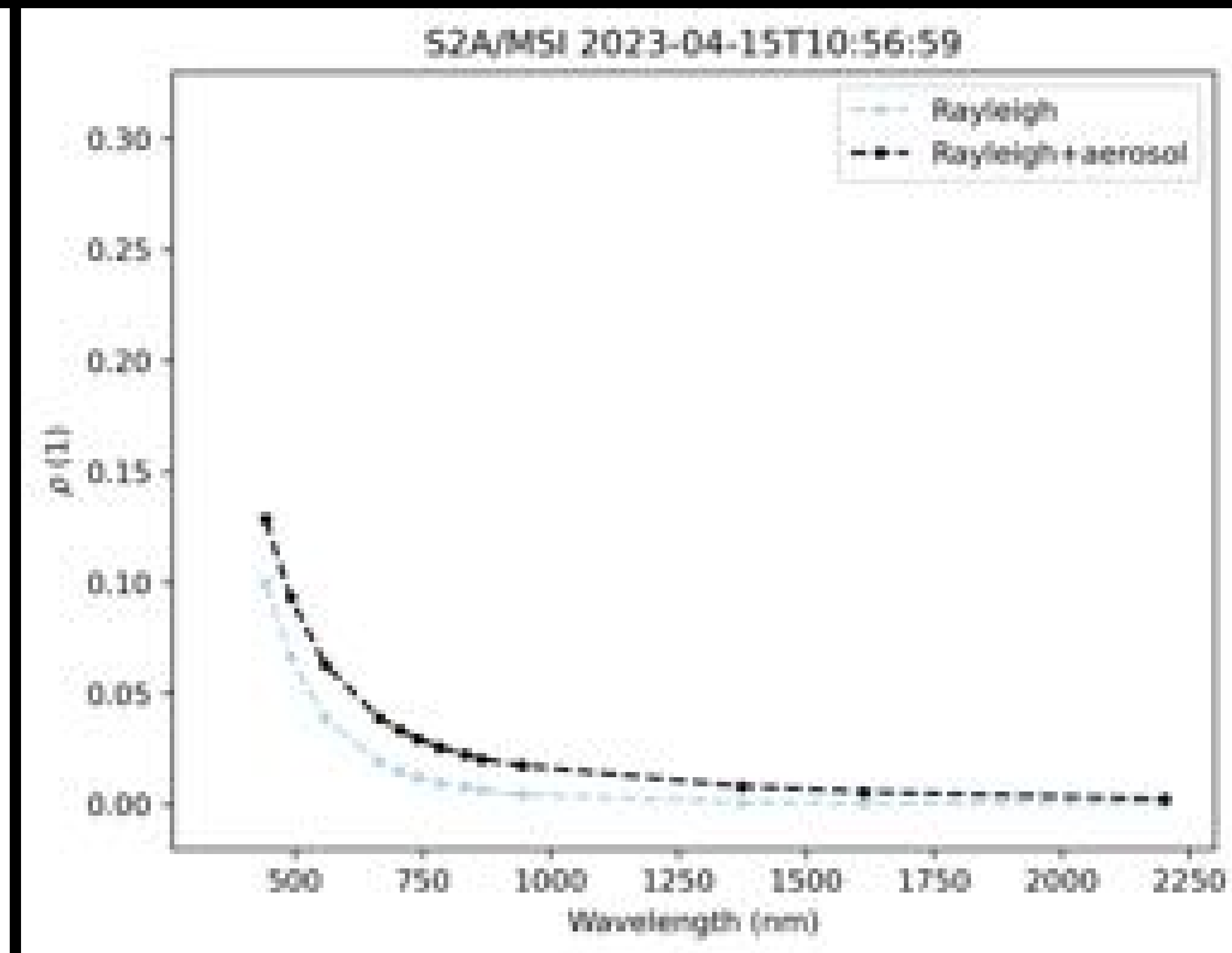
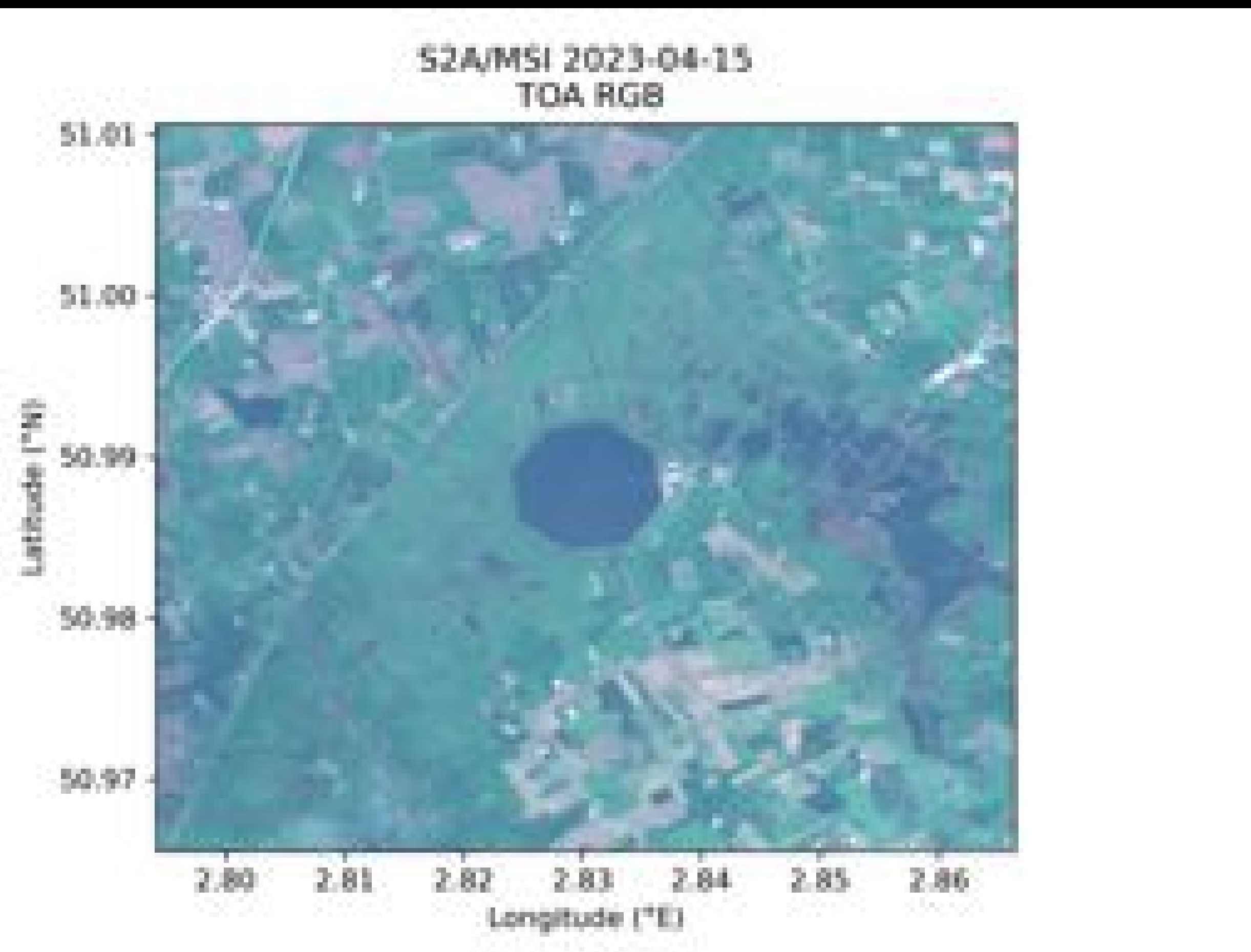
Small inland waters



**Blankaart drinking
water reservoir
~800 m diameter**

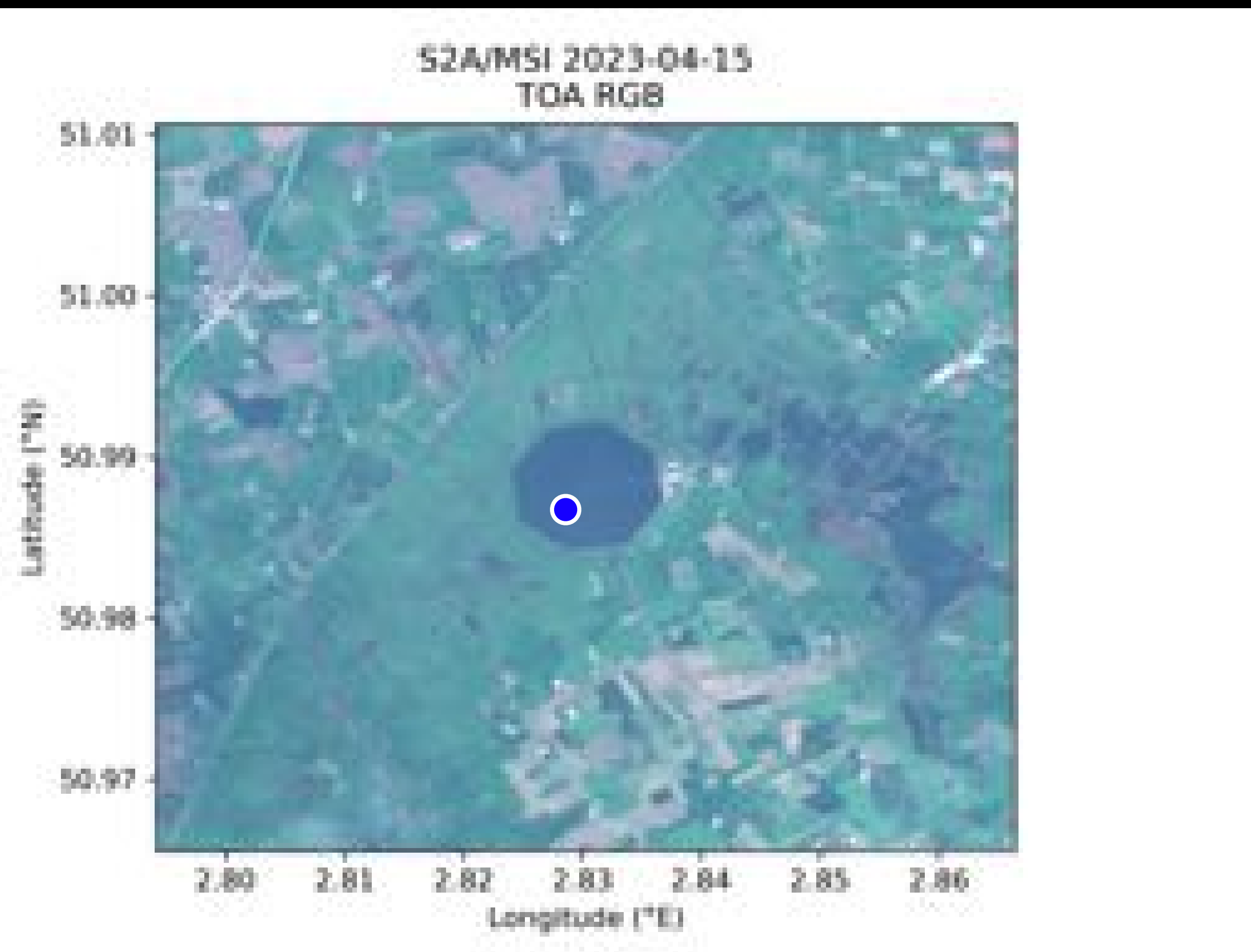
~3x3 km subset

Small inland waters

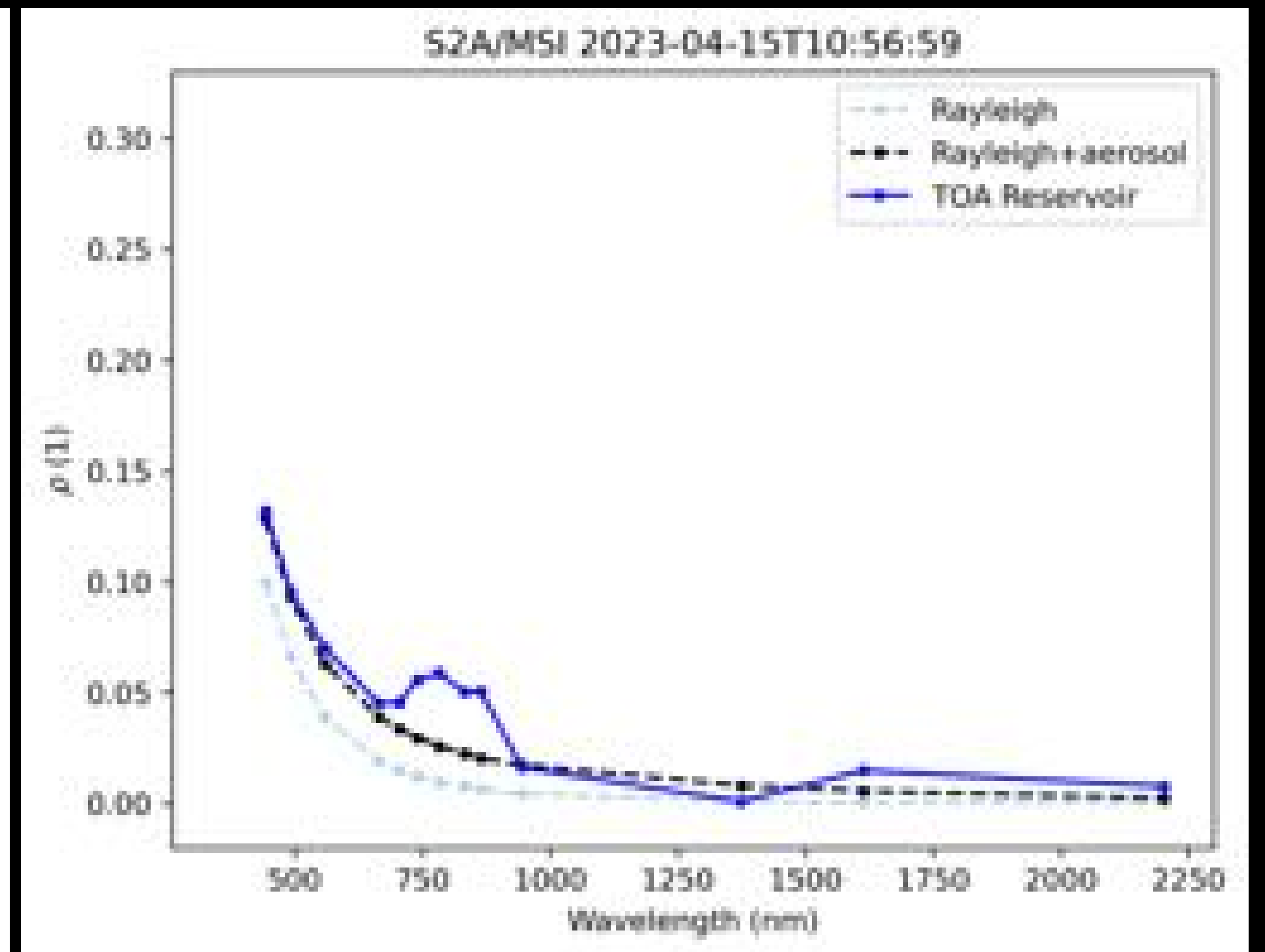


~3x3 km subset

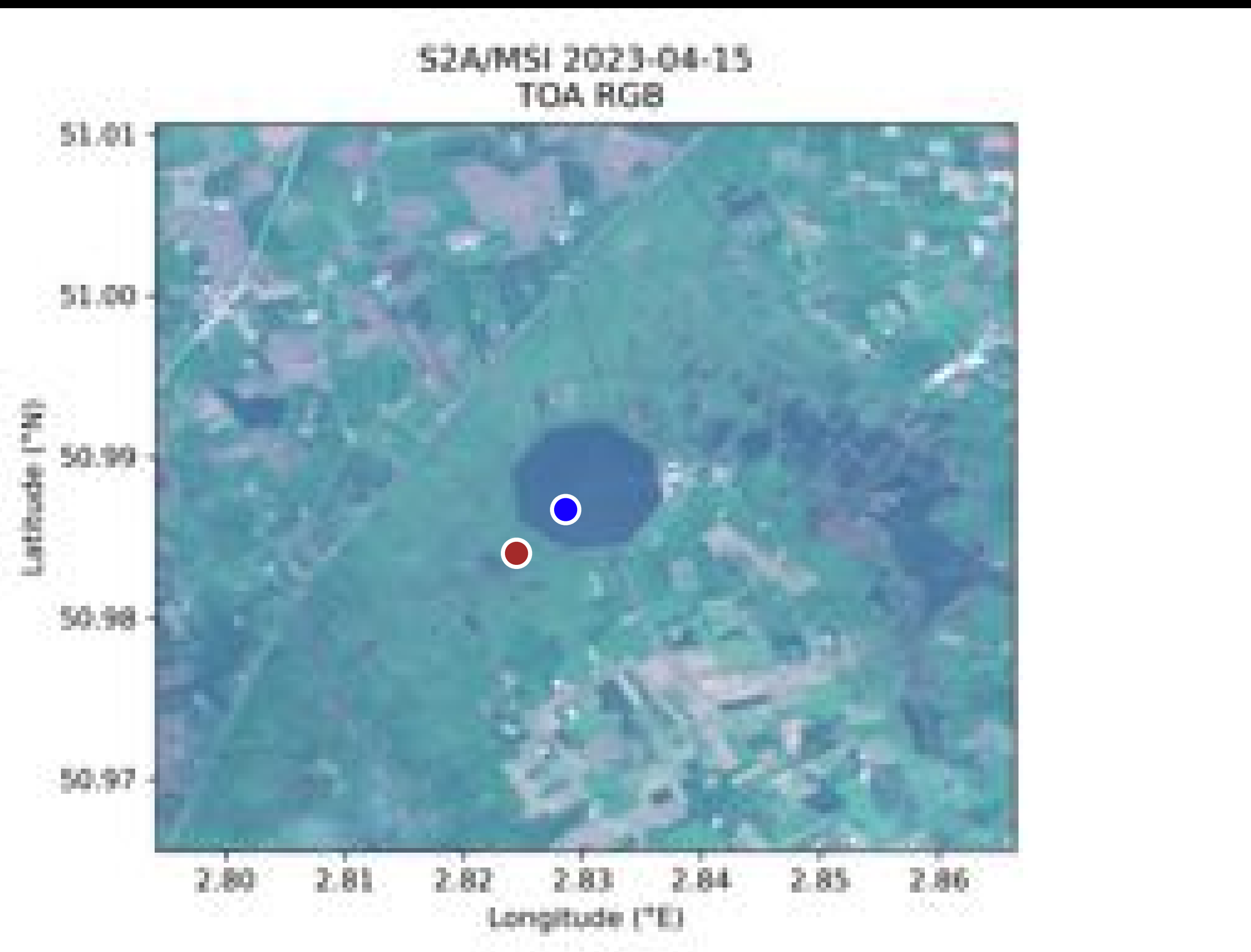
Small inland waters



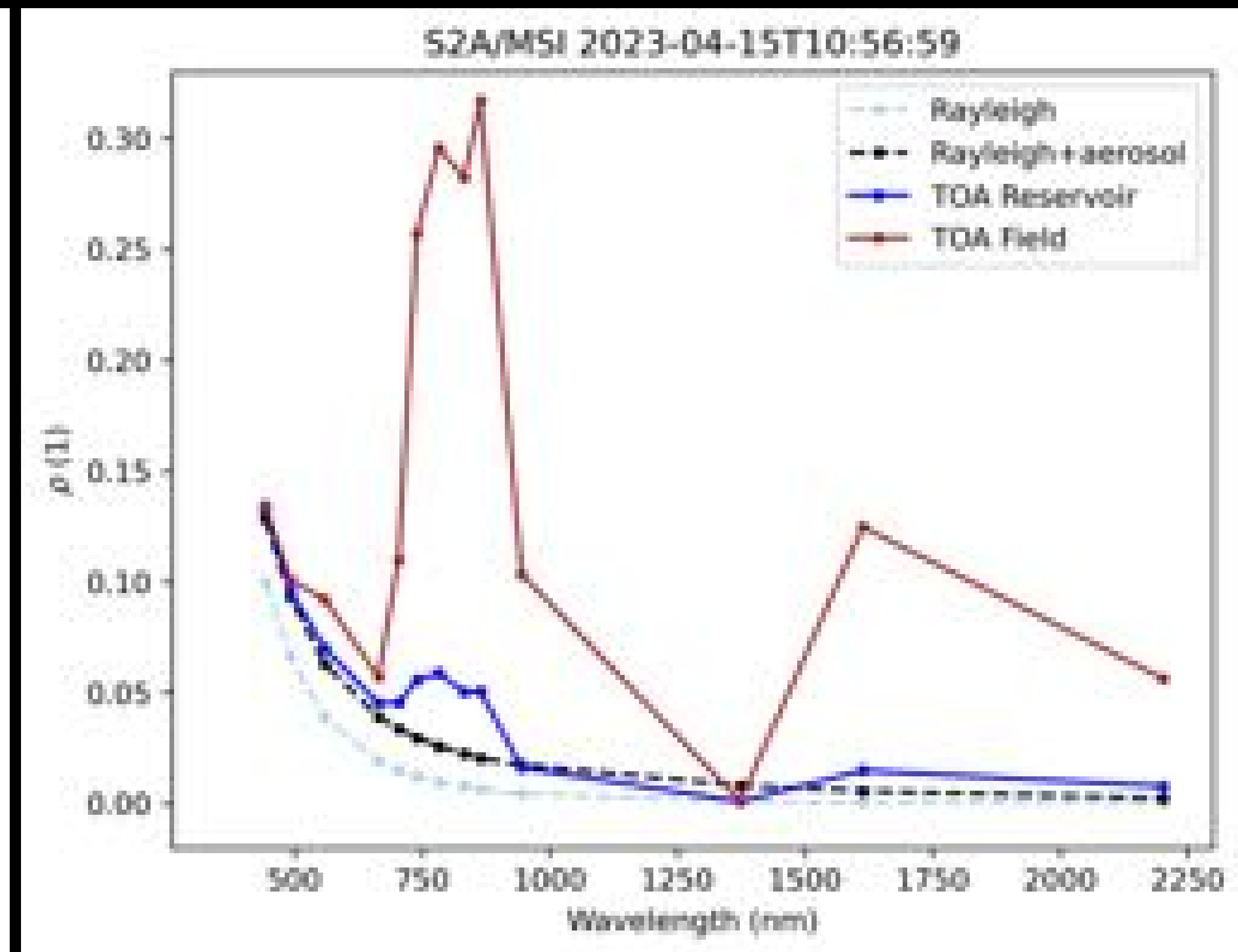
~3x3 km subset



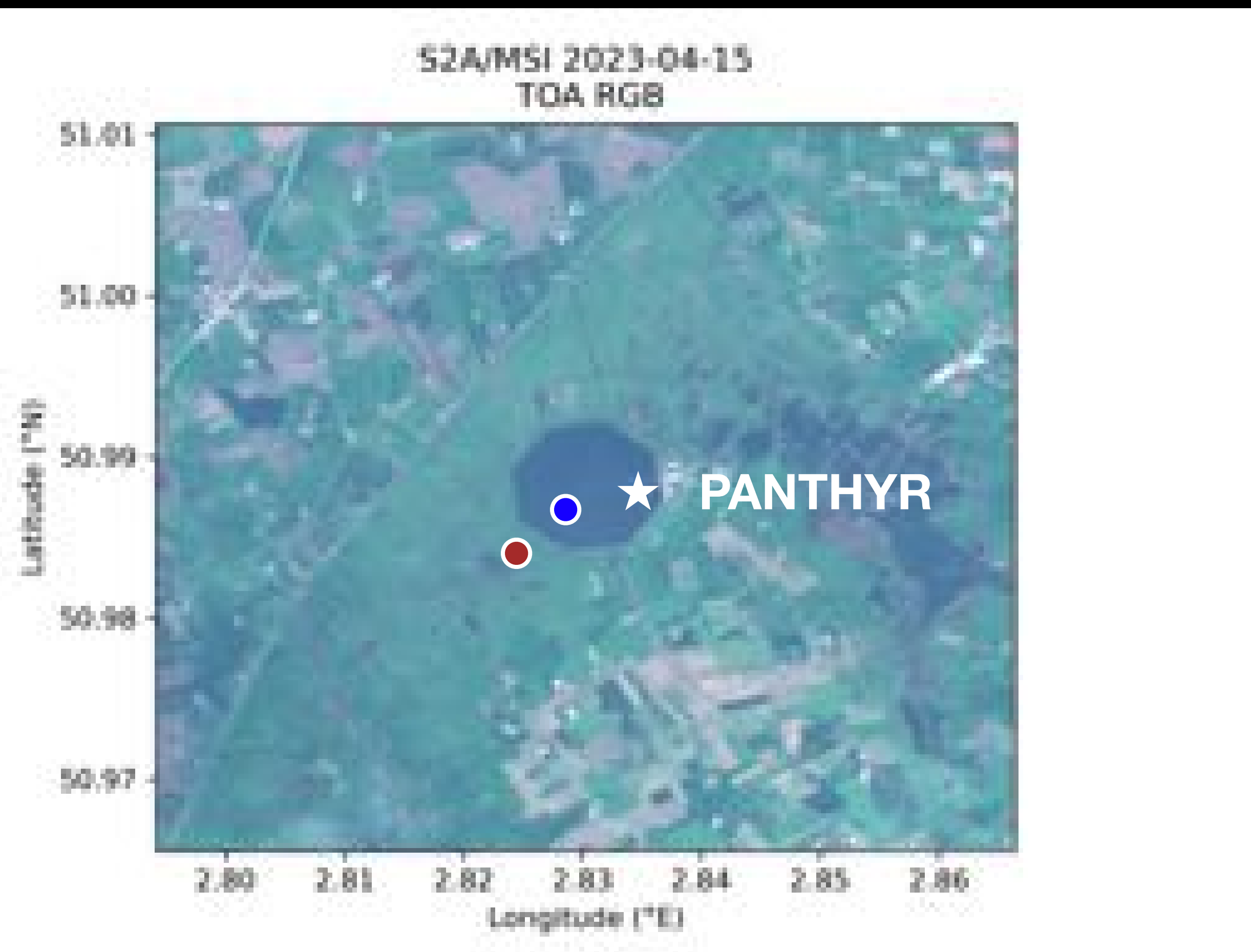
Small inland waters



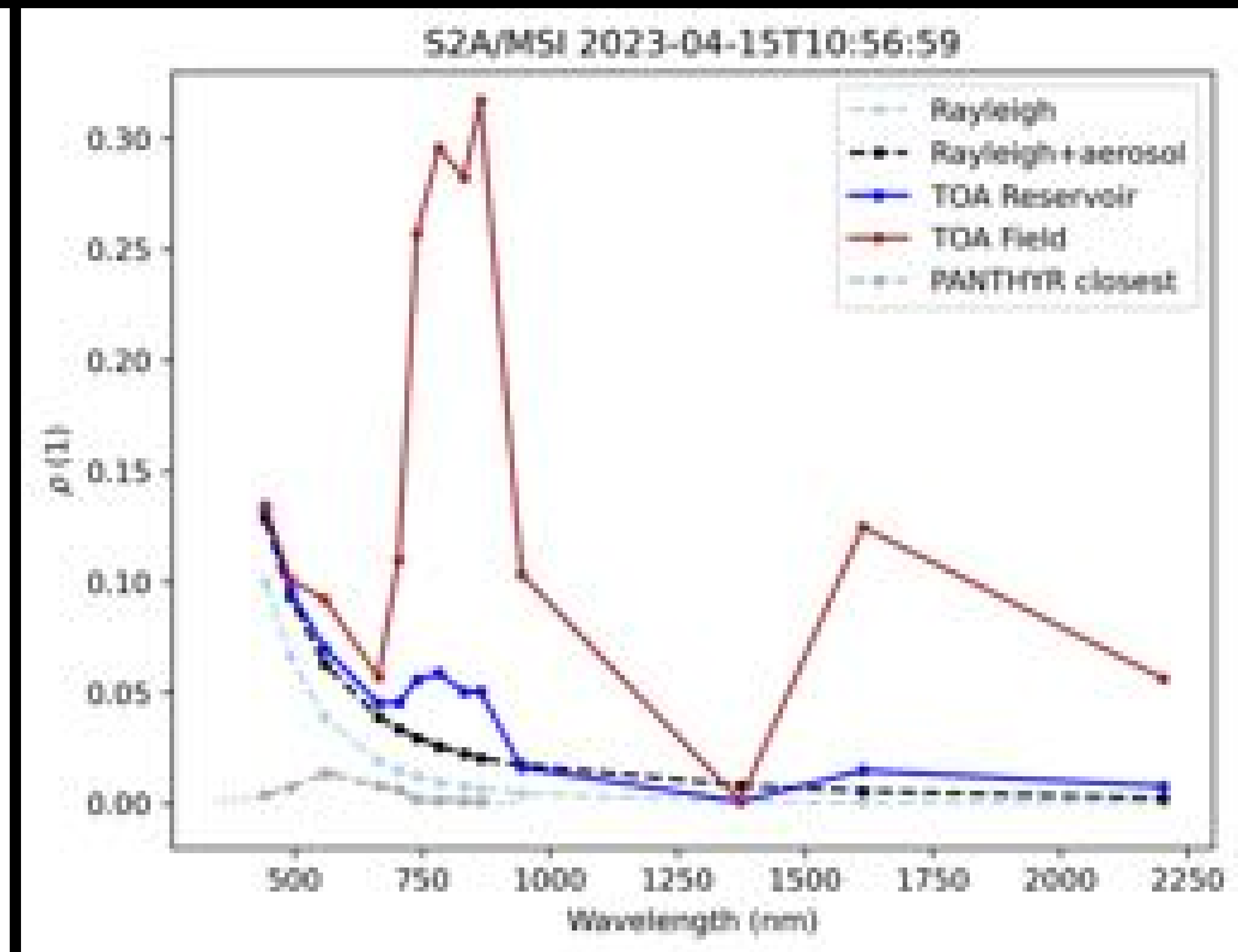
~3x3 km subset



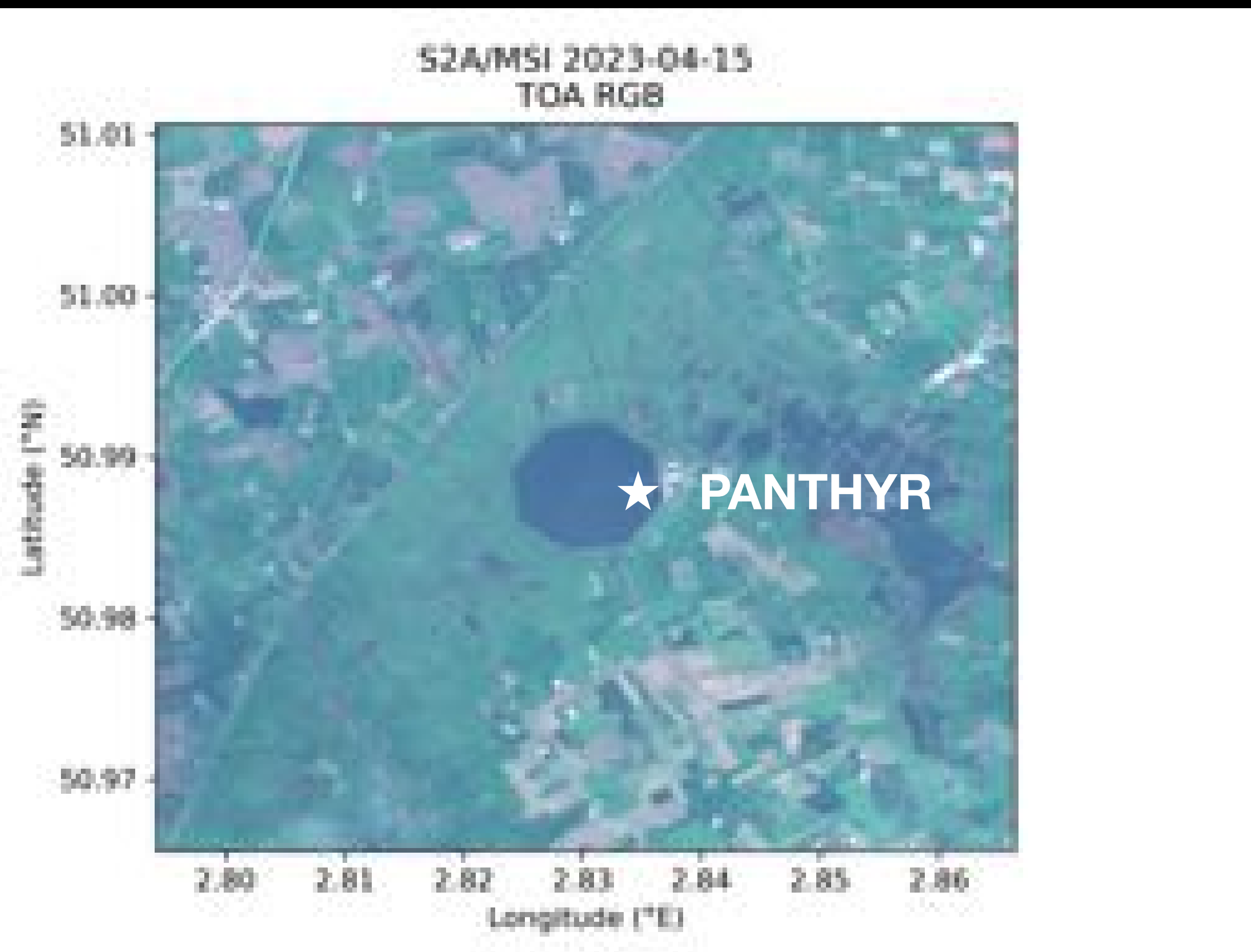
Small inland waters



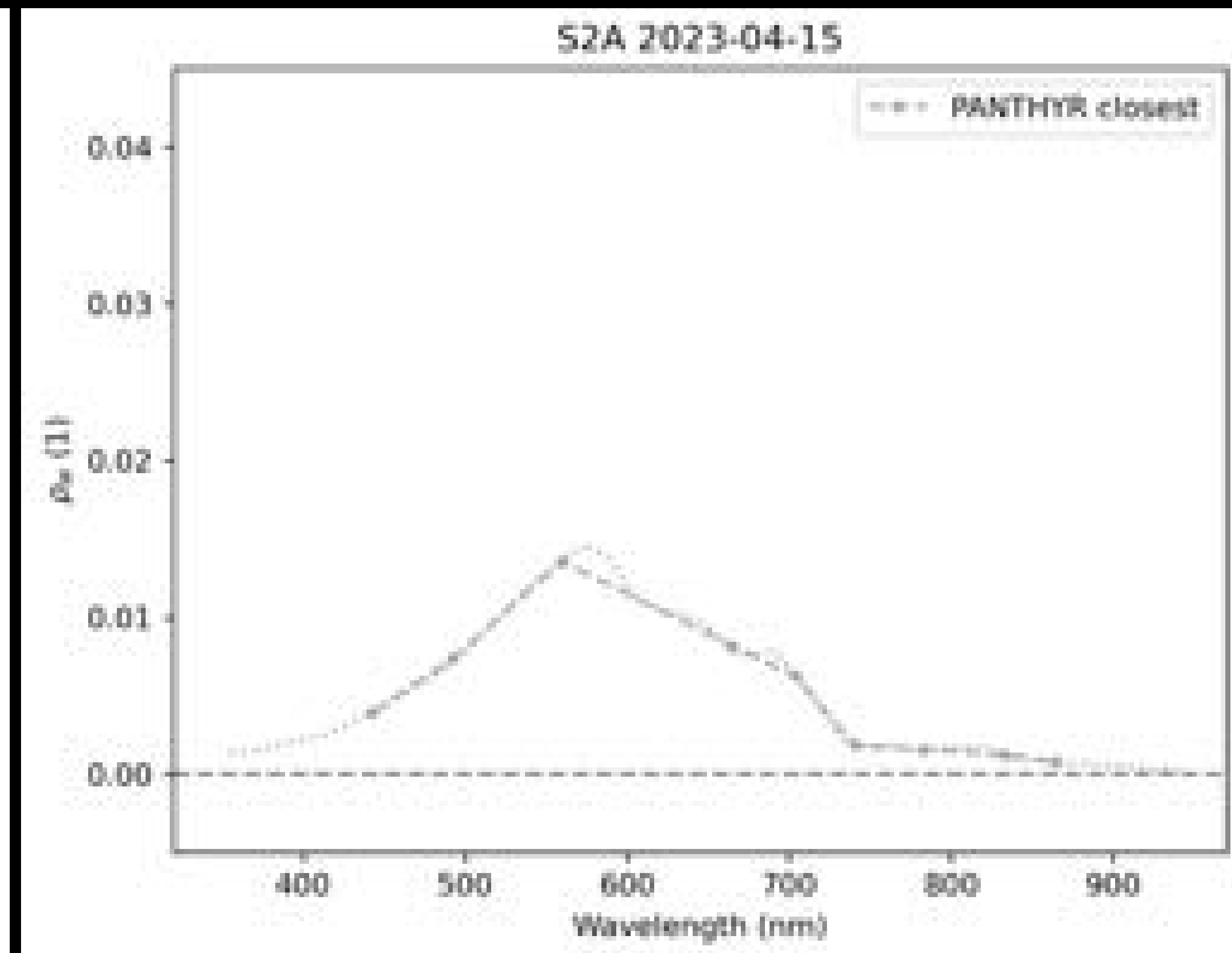
~3x3 km subset



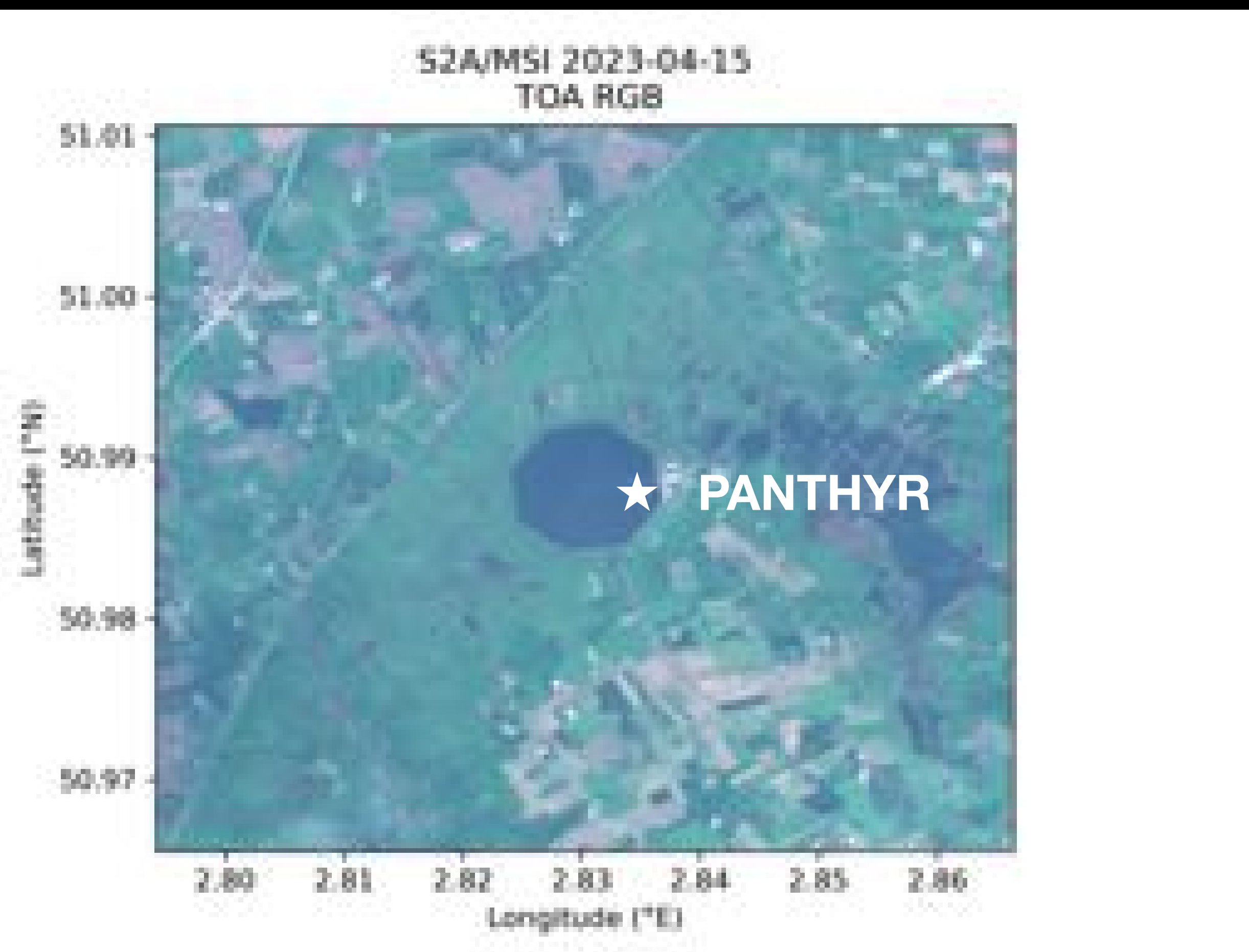
Small inland waters



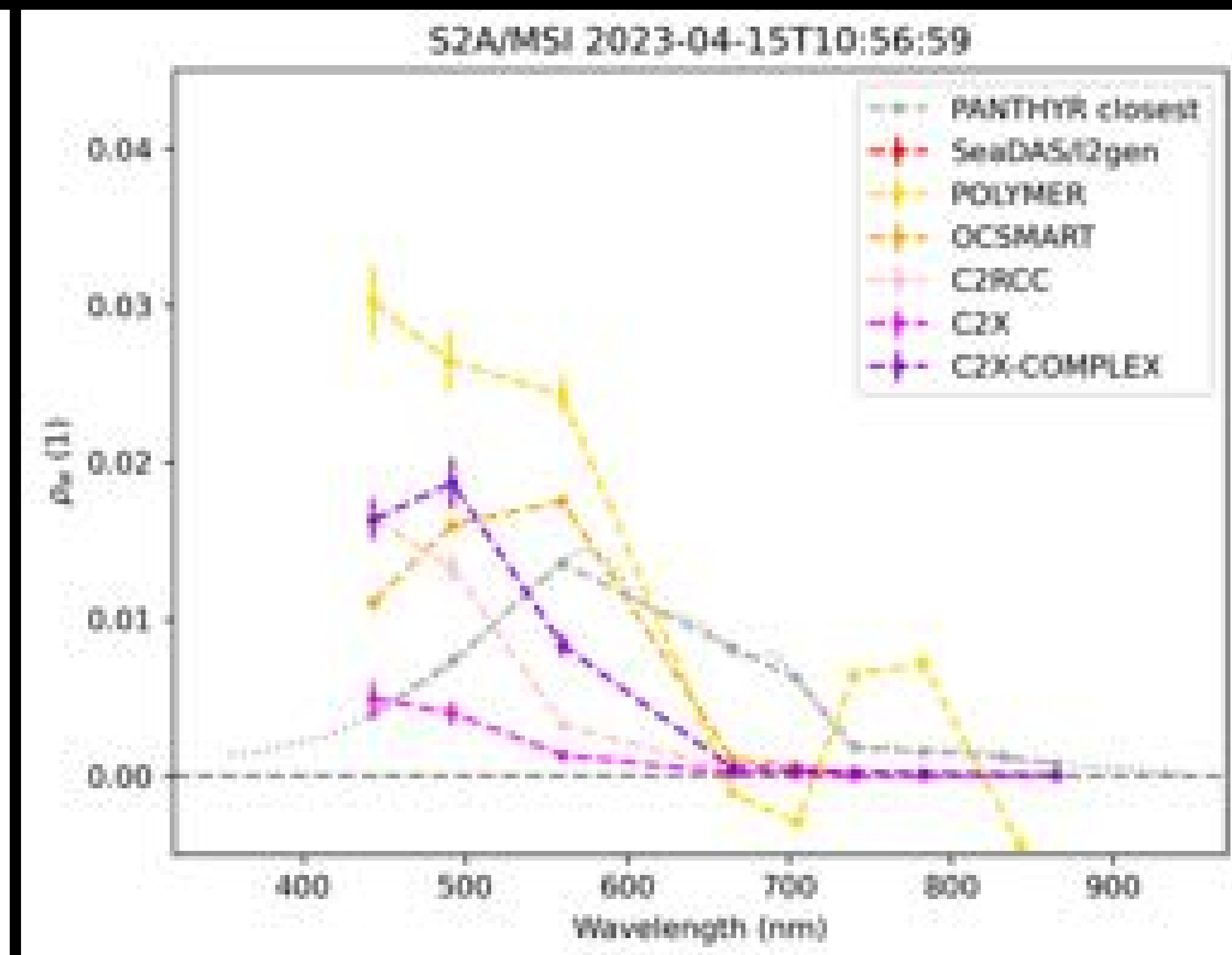
~3x3 km subset



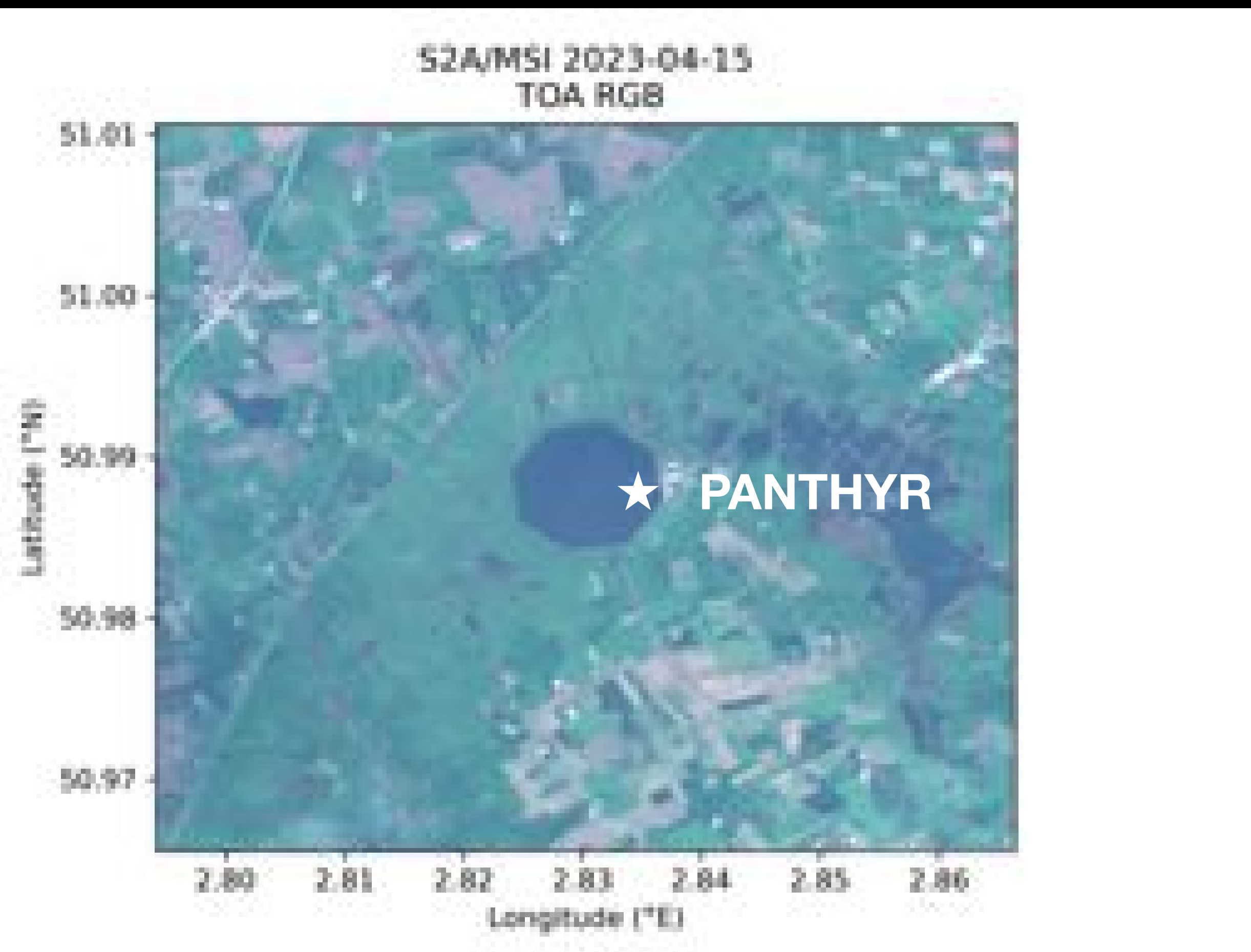
Small inland waters



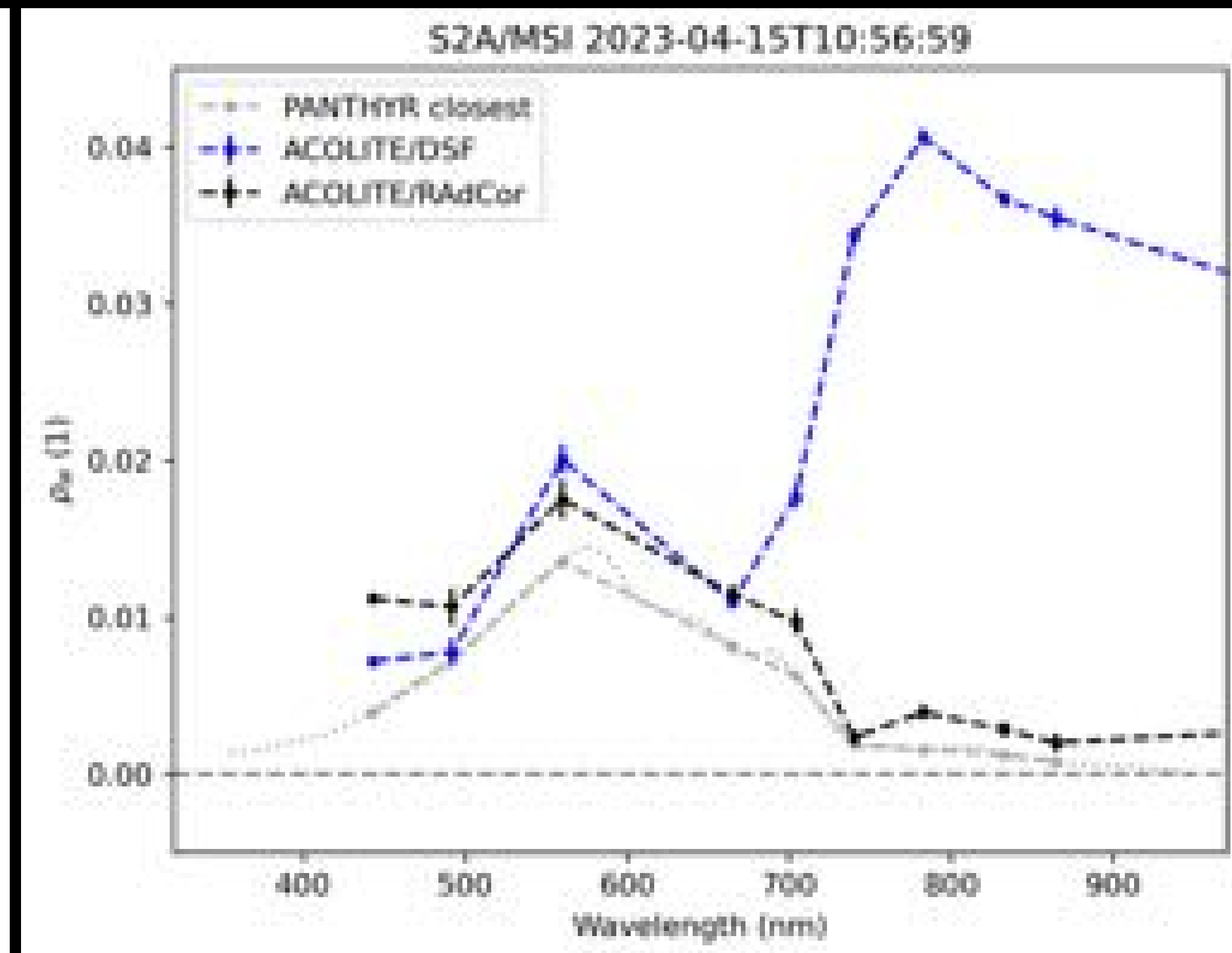
~3x3 km subset



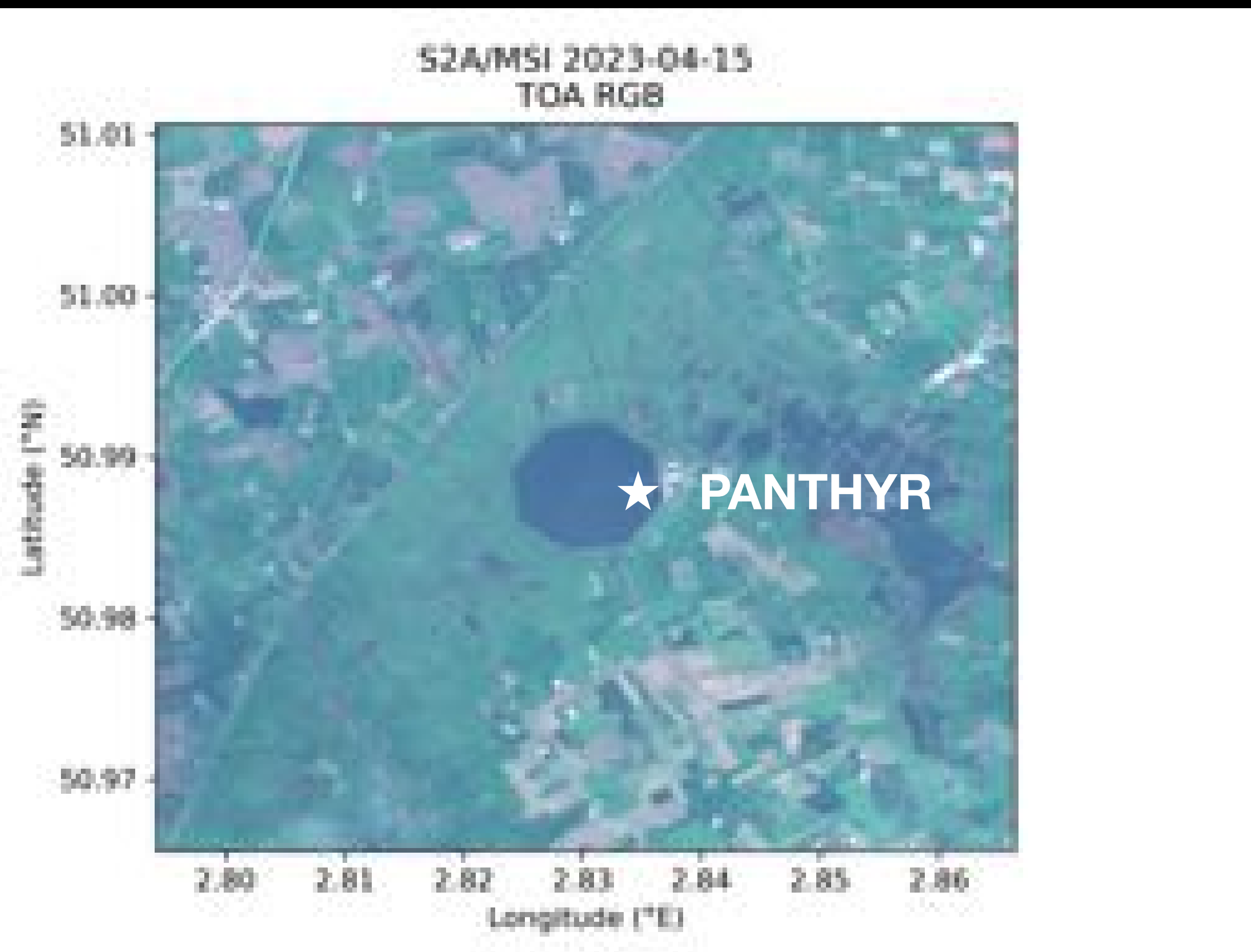
Small inland waters



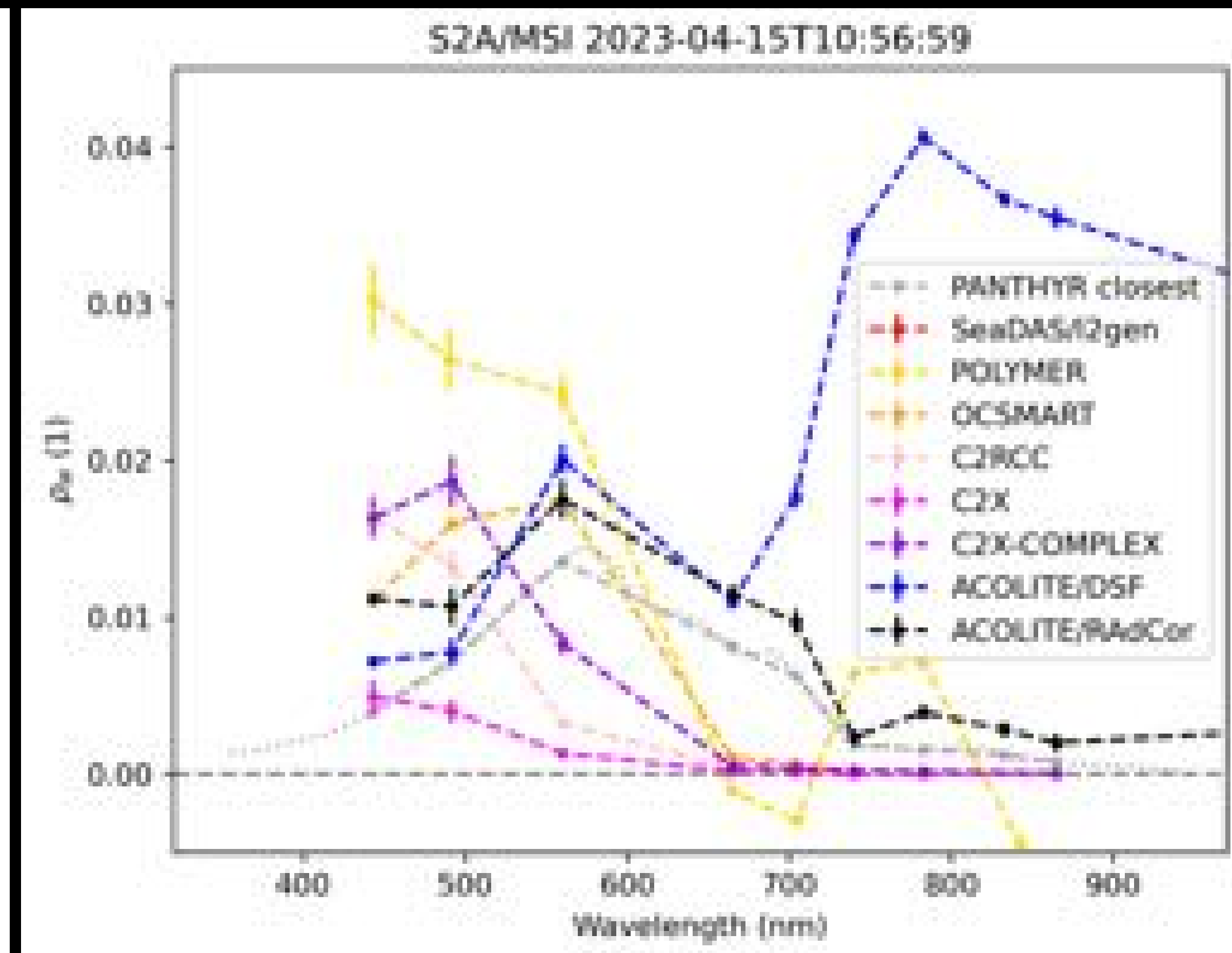
~3x3 km subset



Small inland waters

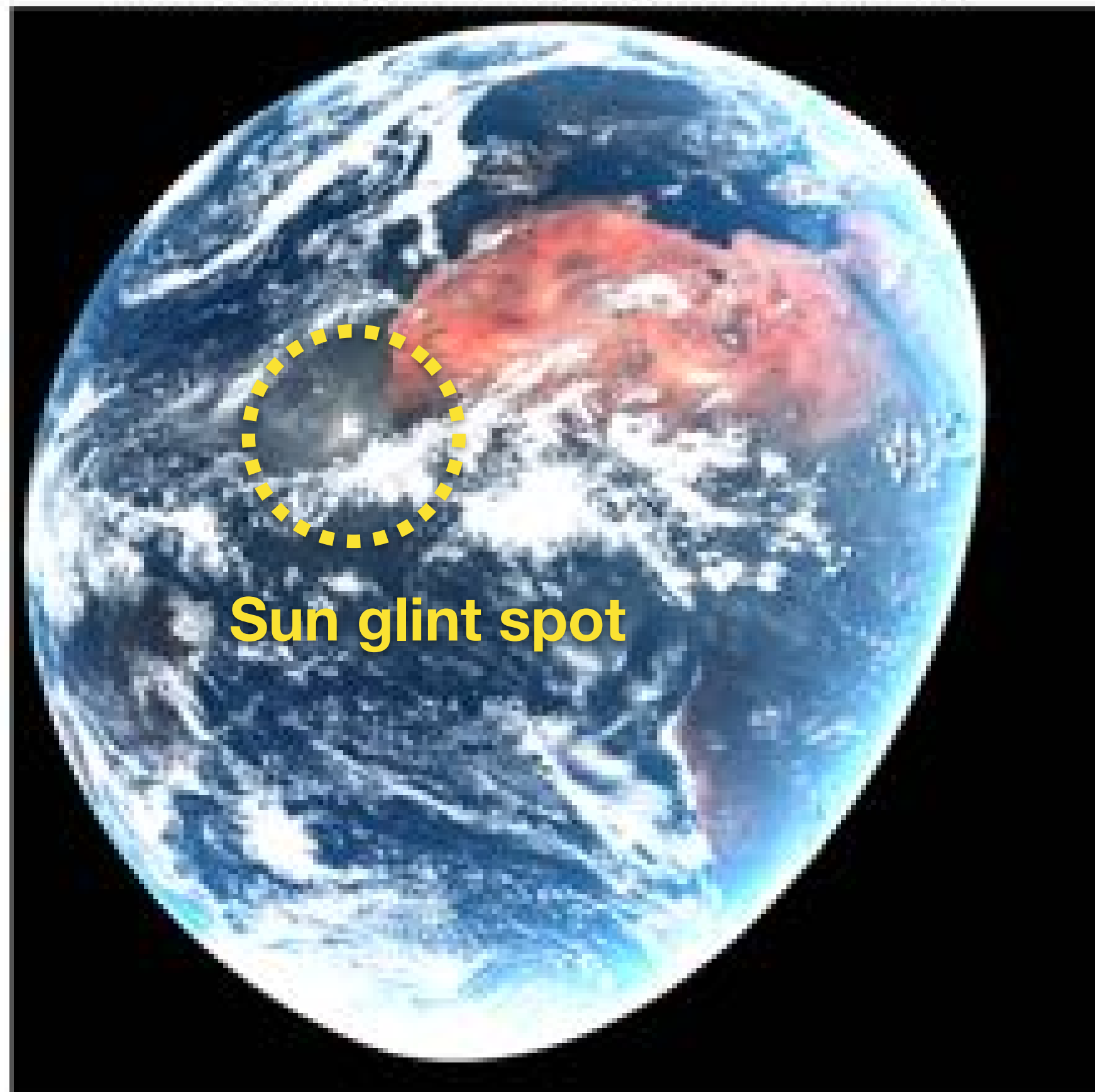


~3x3 km subset

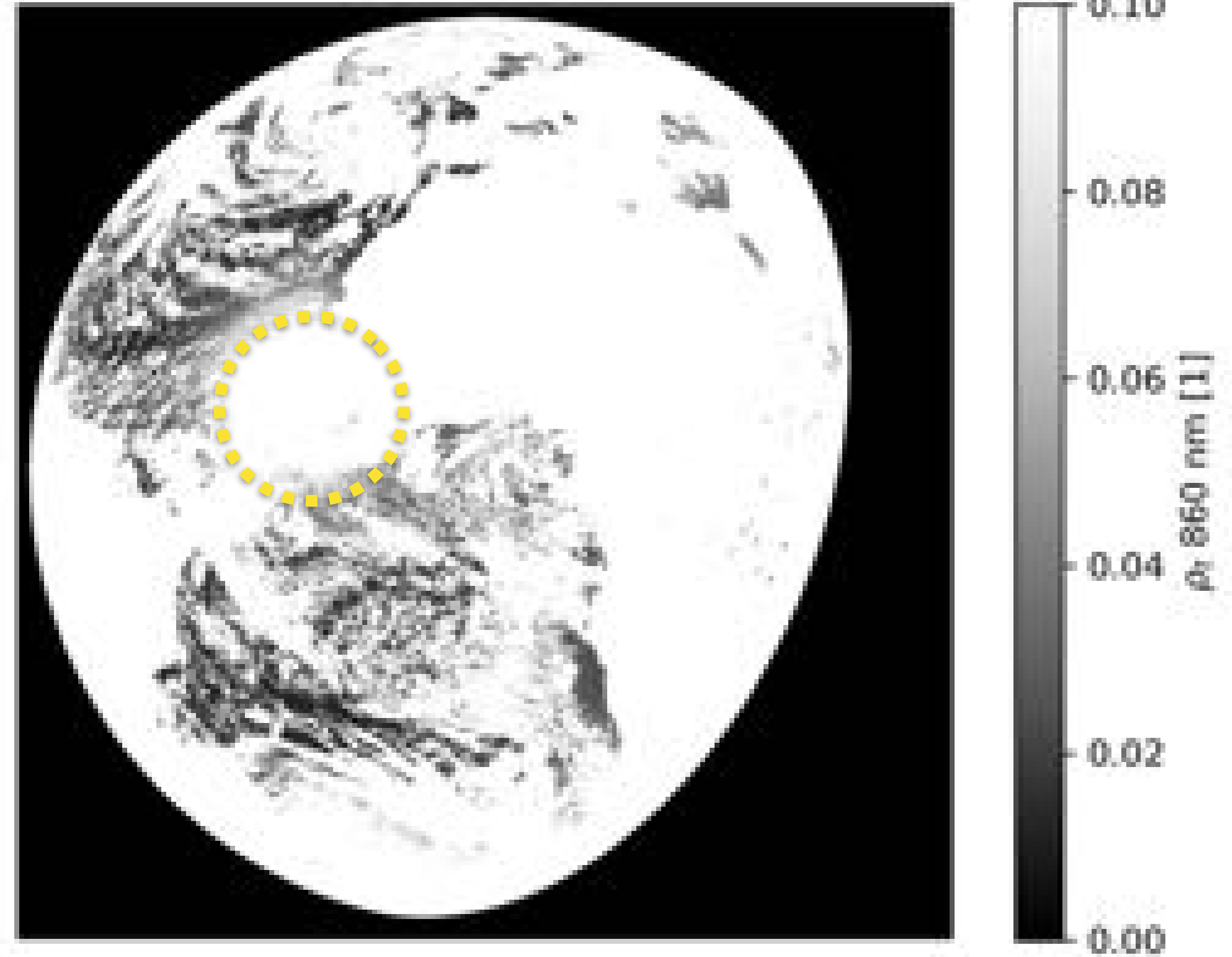


Glint correction

MTG-I1/FCI 2026-05-25 15:00:00
 ρ_t RGB (637 nm, 508 nm, 447 nm)



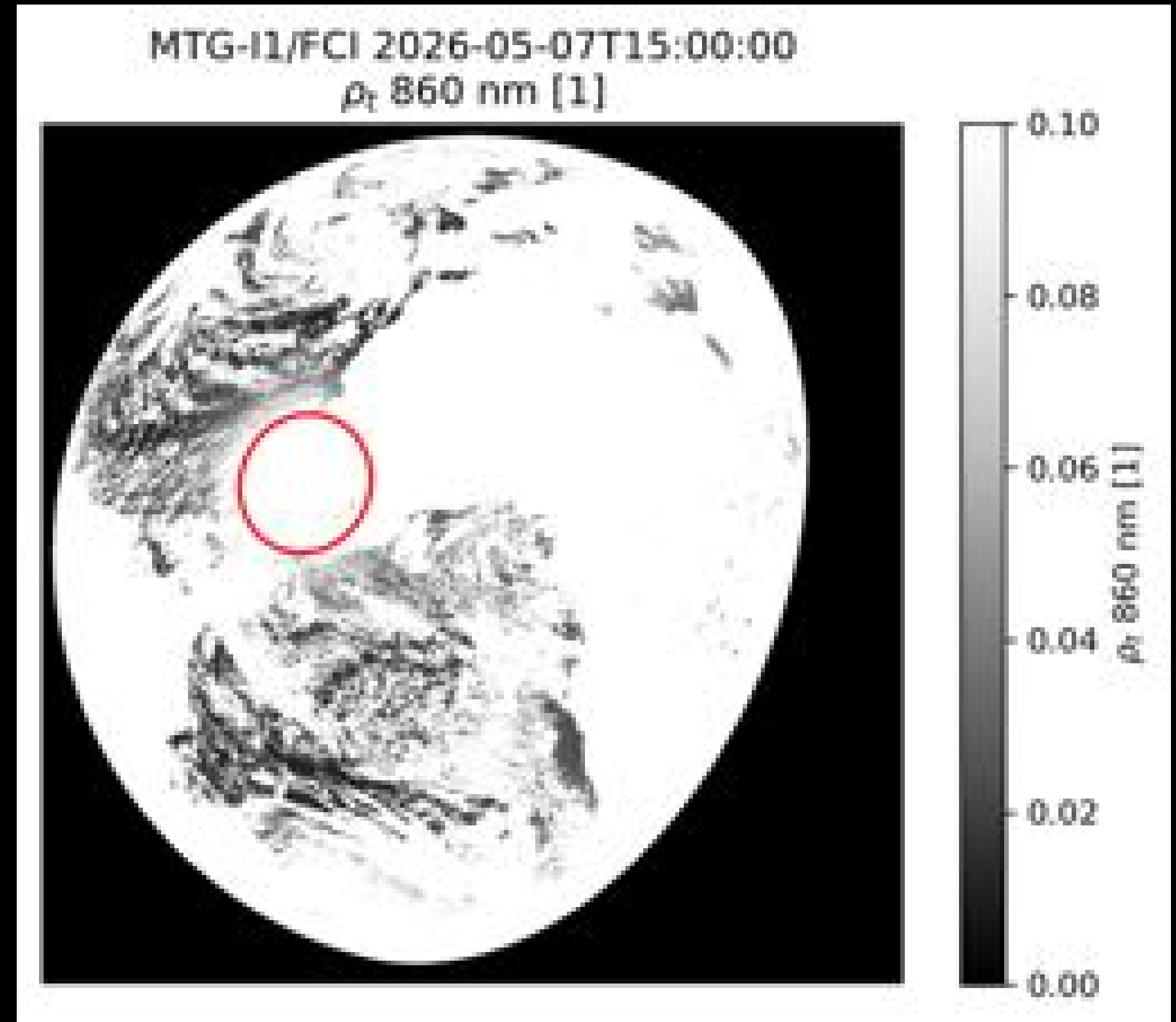
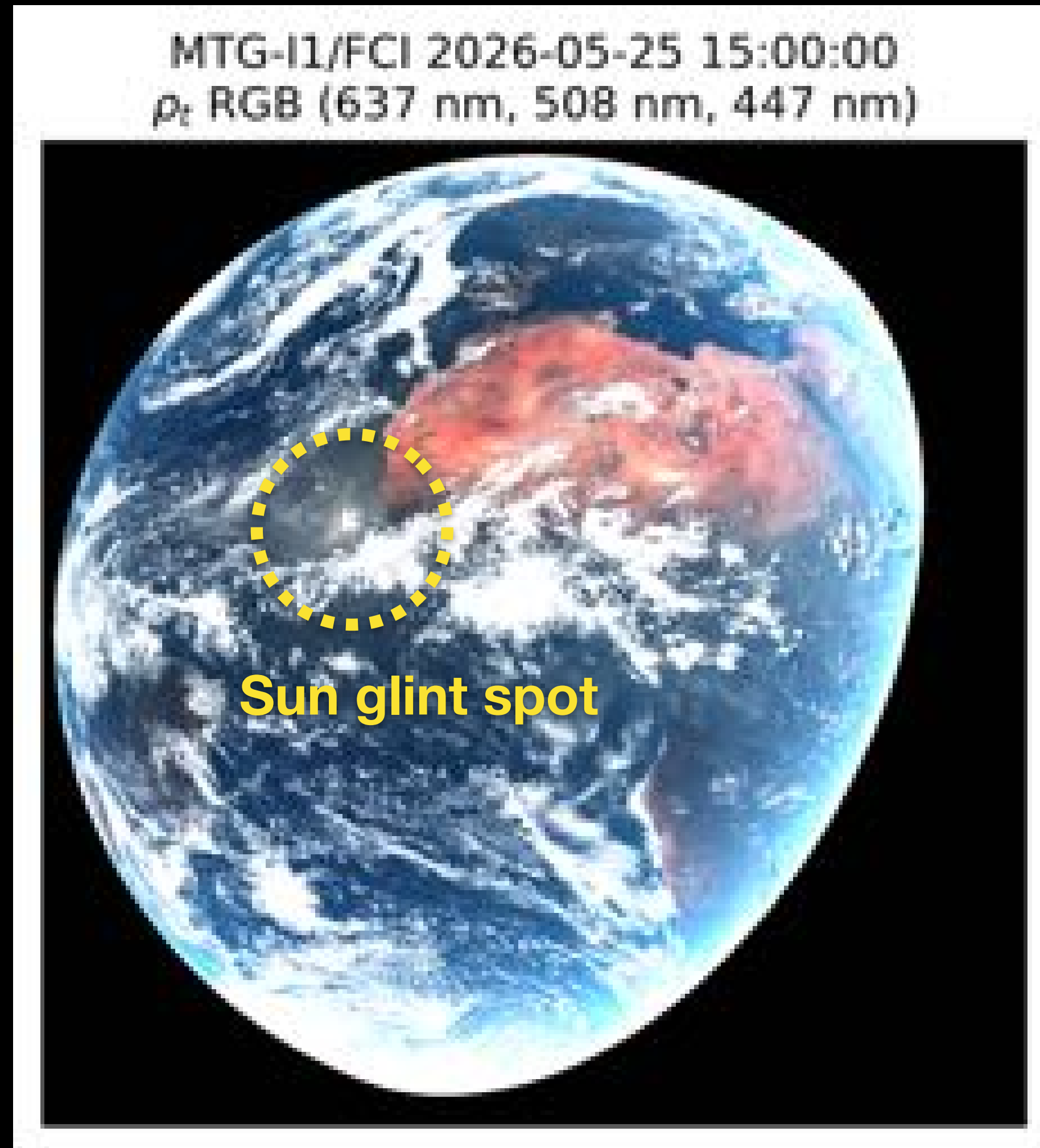
MTG-I1/FCI 2026-05-07T15:00:00
 ρ_t 860 nm [1]



Glint correction

Geometry + wind speed

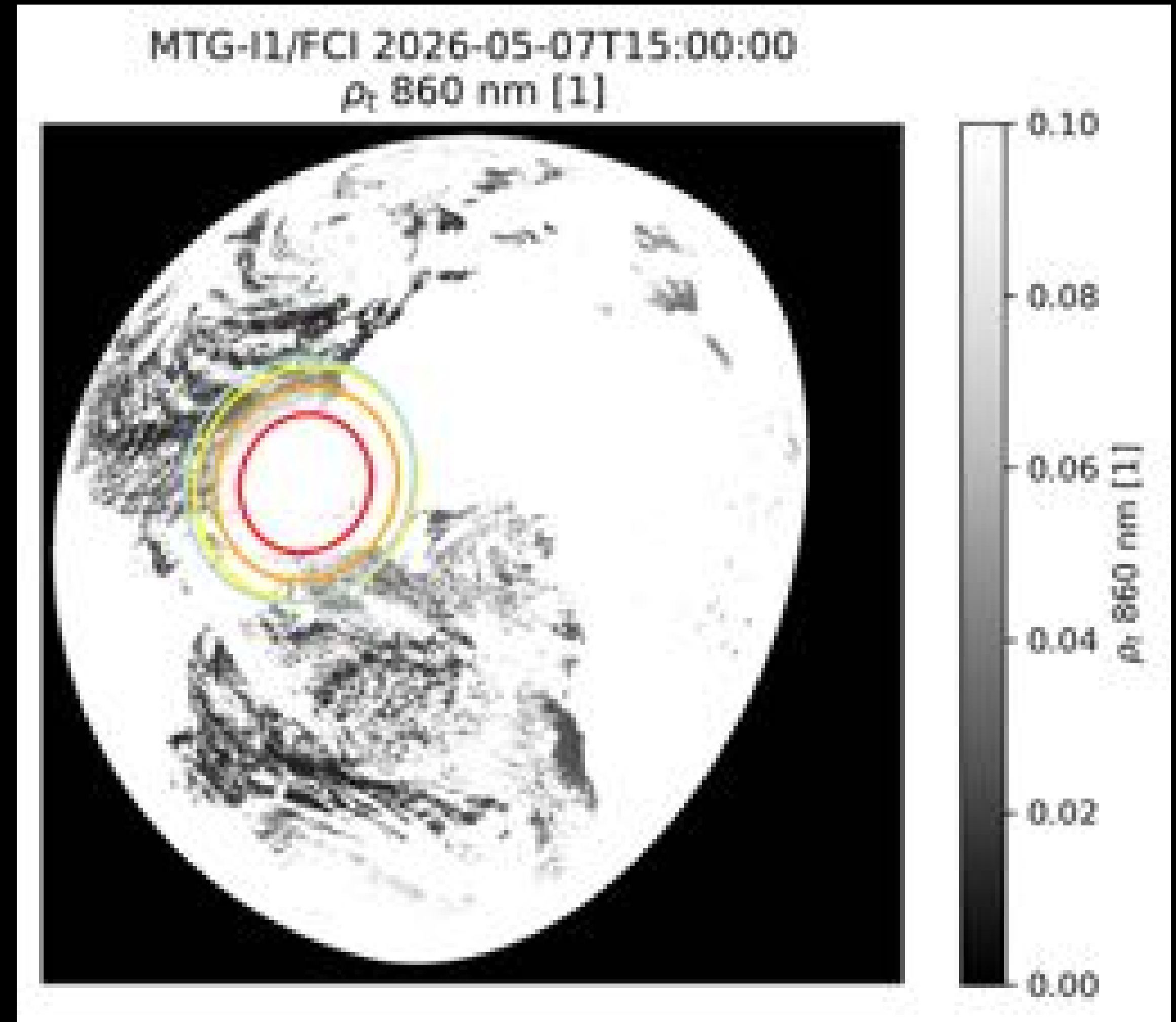
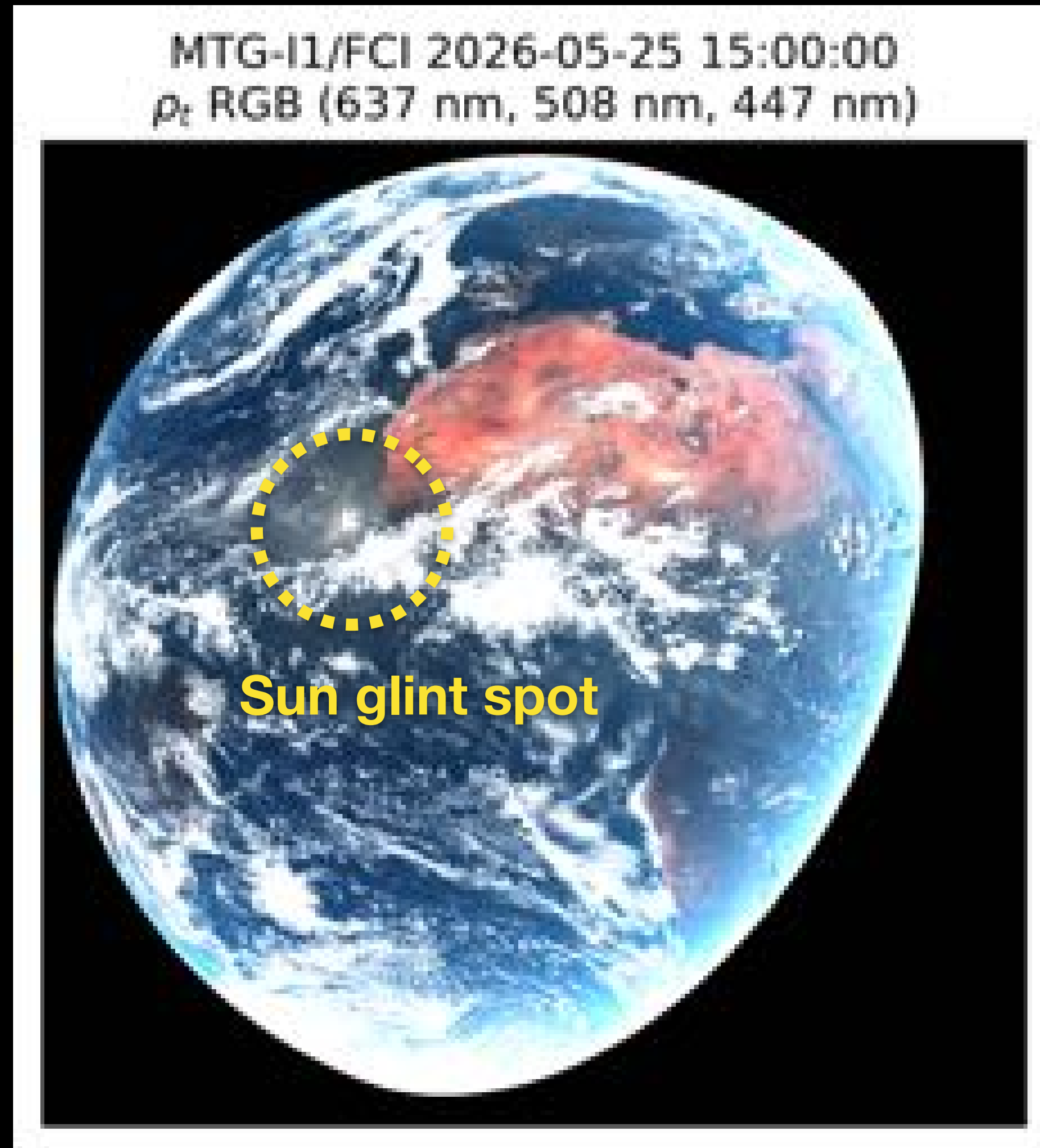
Cox and Munk **1 m/s**



Glint correction

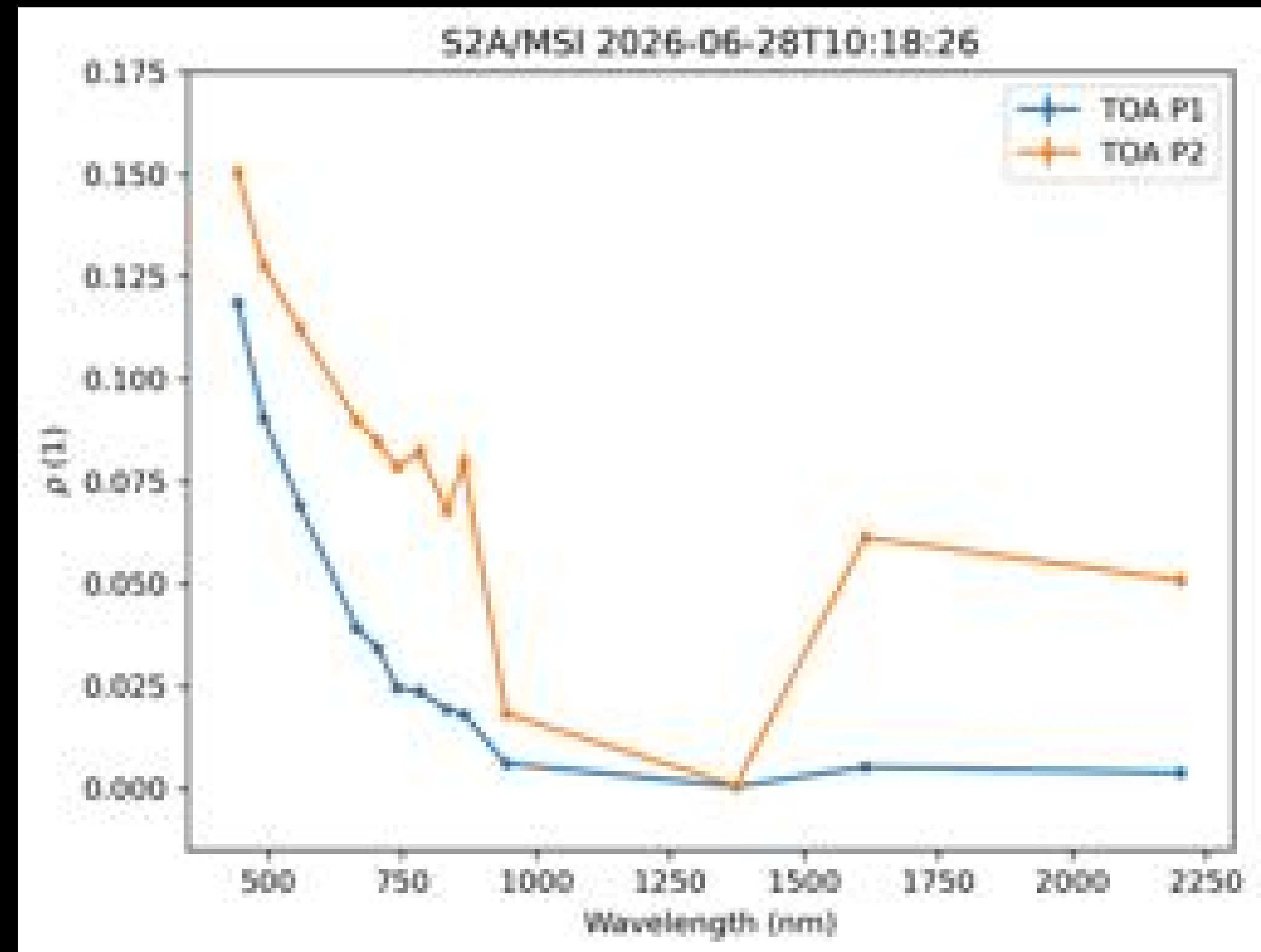
Geometry + wind speed

Cox and Munk 1 m/s 4 m/s 10 m/s 20 m/s



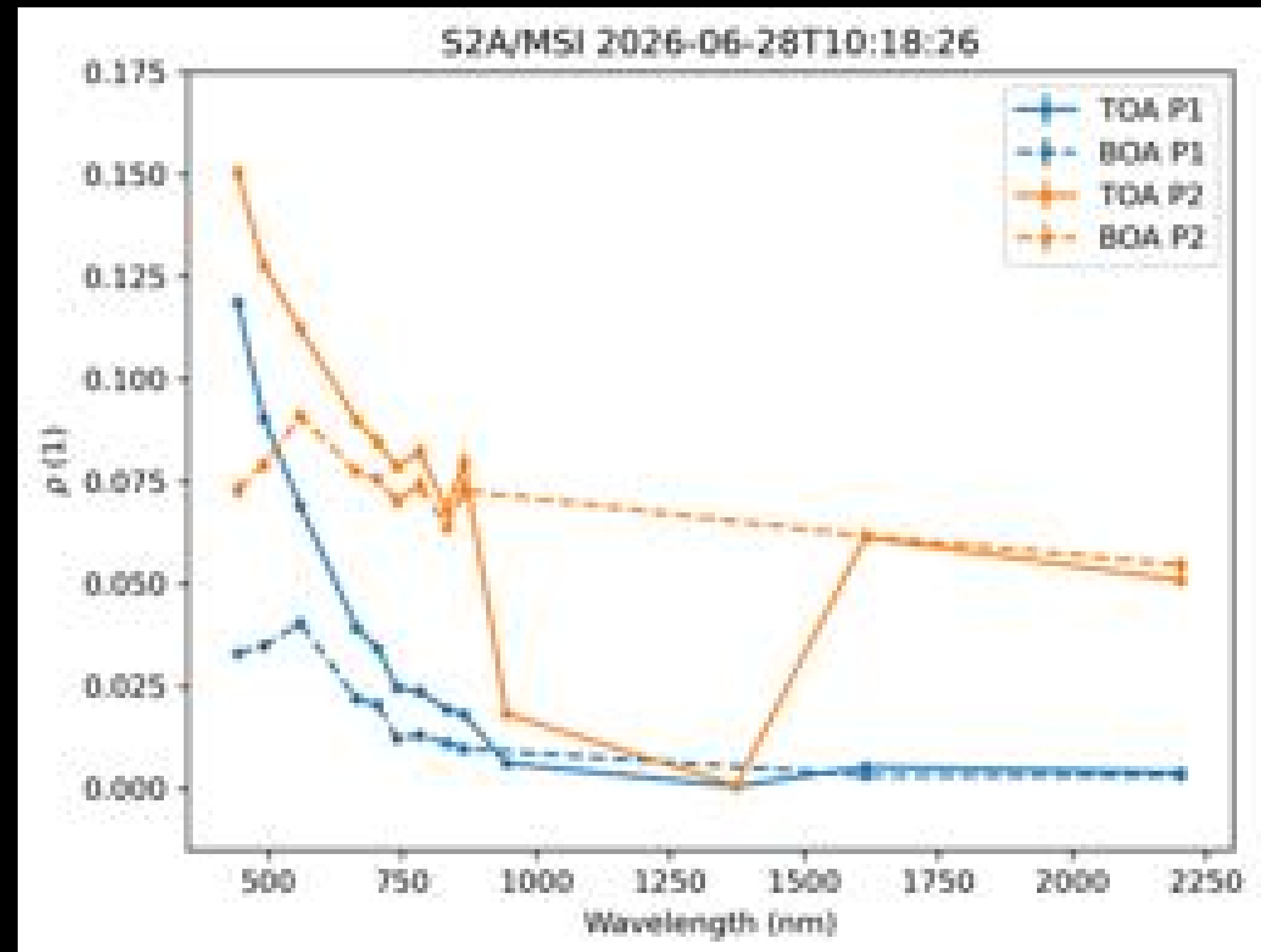
Glint correction

S2A/MSI 2026-06-28 10:18:26
 ρ_s RGB



Glint correction

S2A/MSI 2026-06-28 10:18:26
 ρ_s RGB

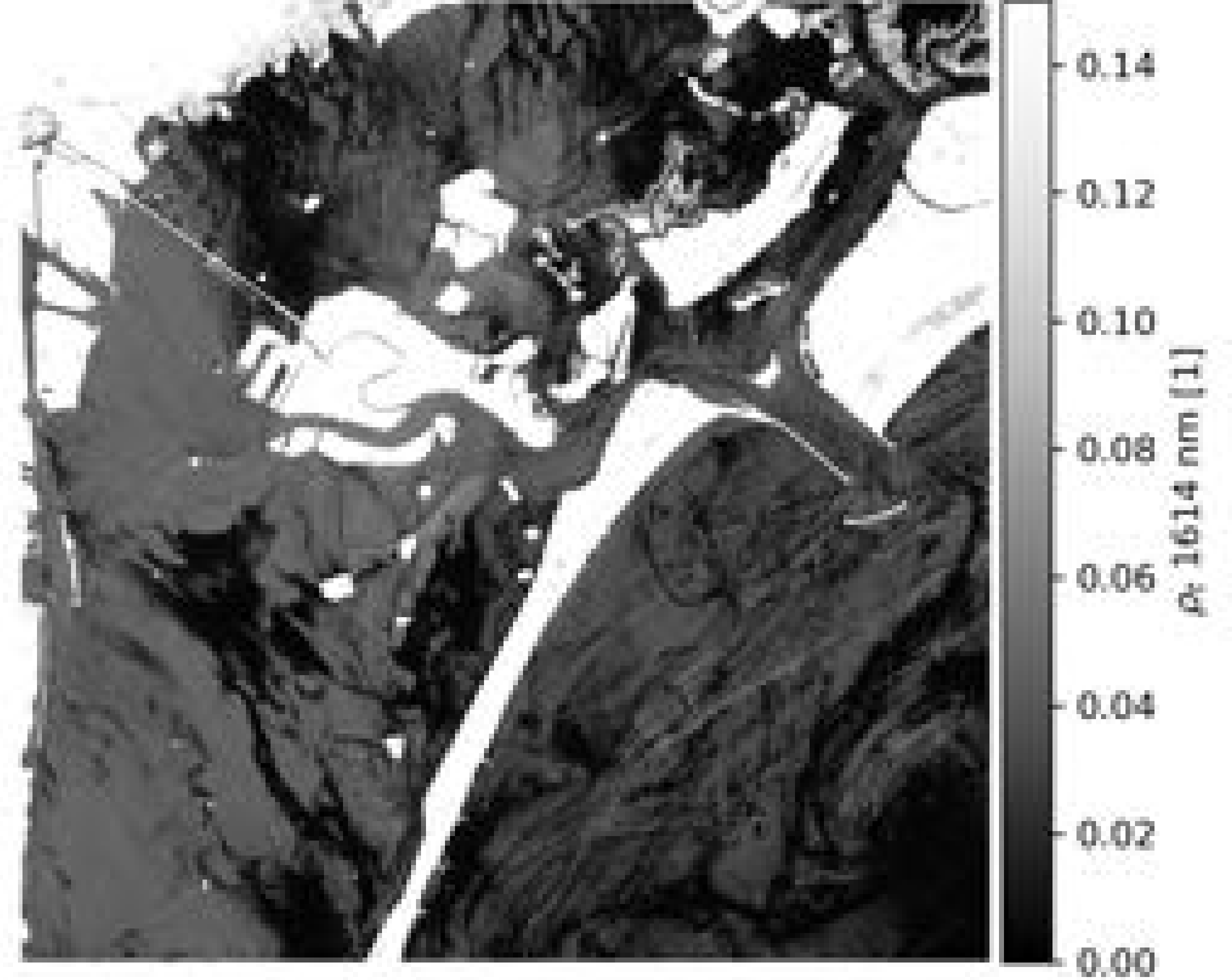


Glint correction

S2A/MSI 2026-06-28 10:18:26
 ρ_s RGB

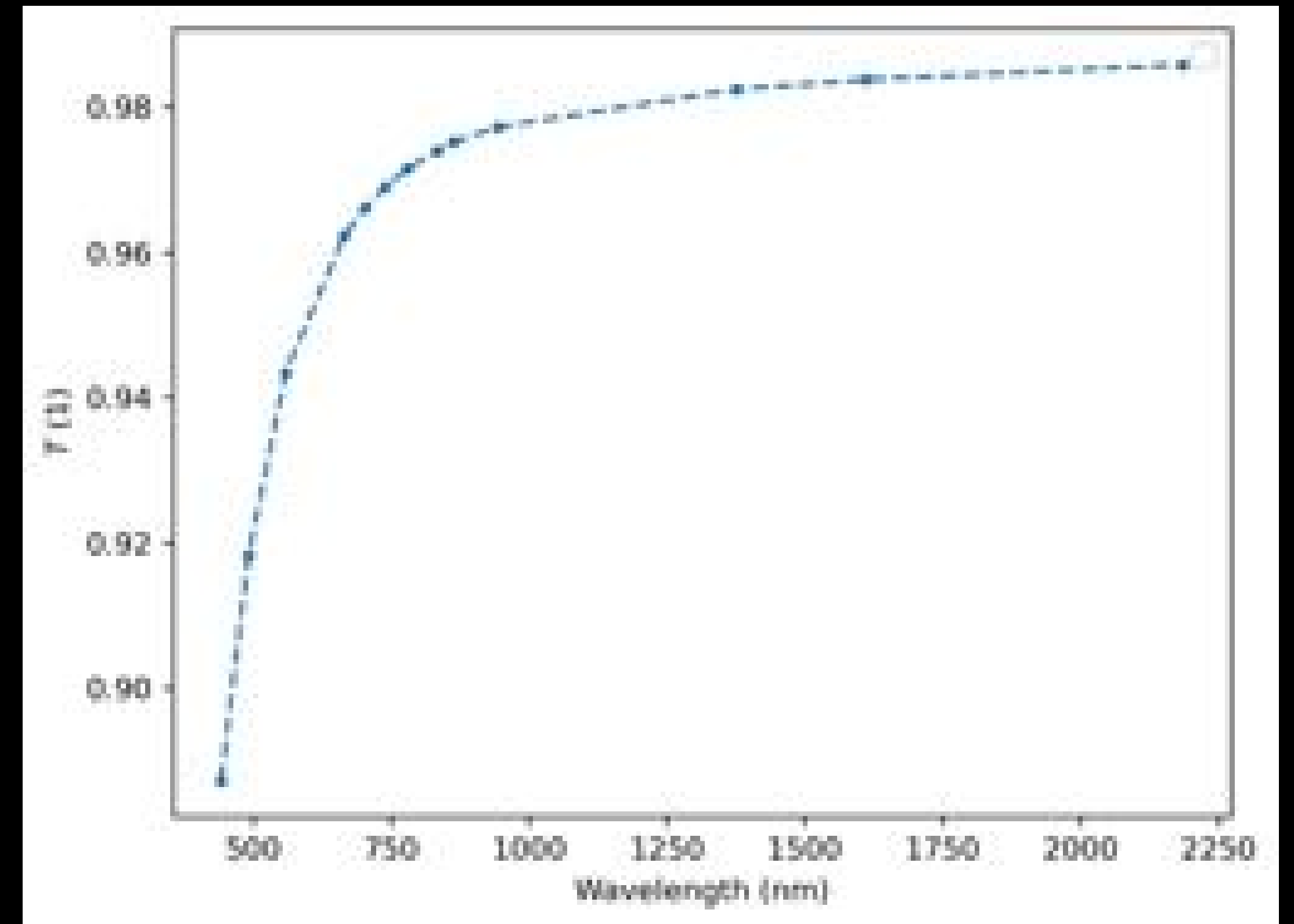
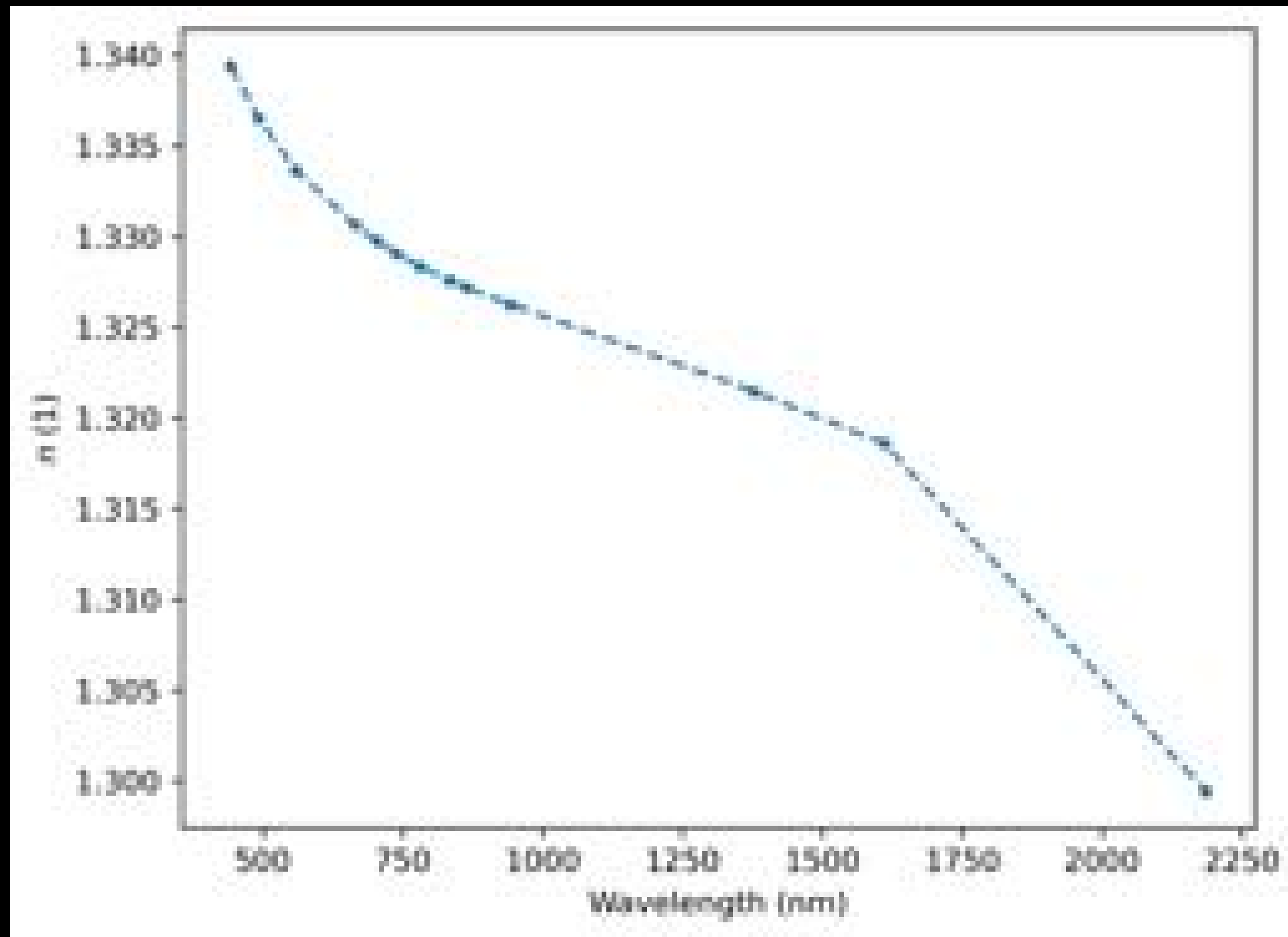


S2A/MSI 2026-06-28 10:18:26
 ρ_r 1614 nm [1]



Glint correction

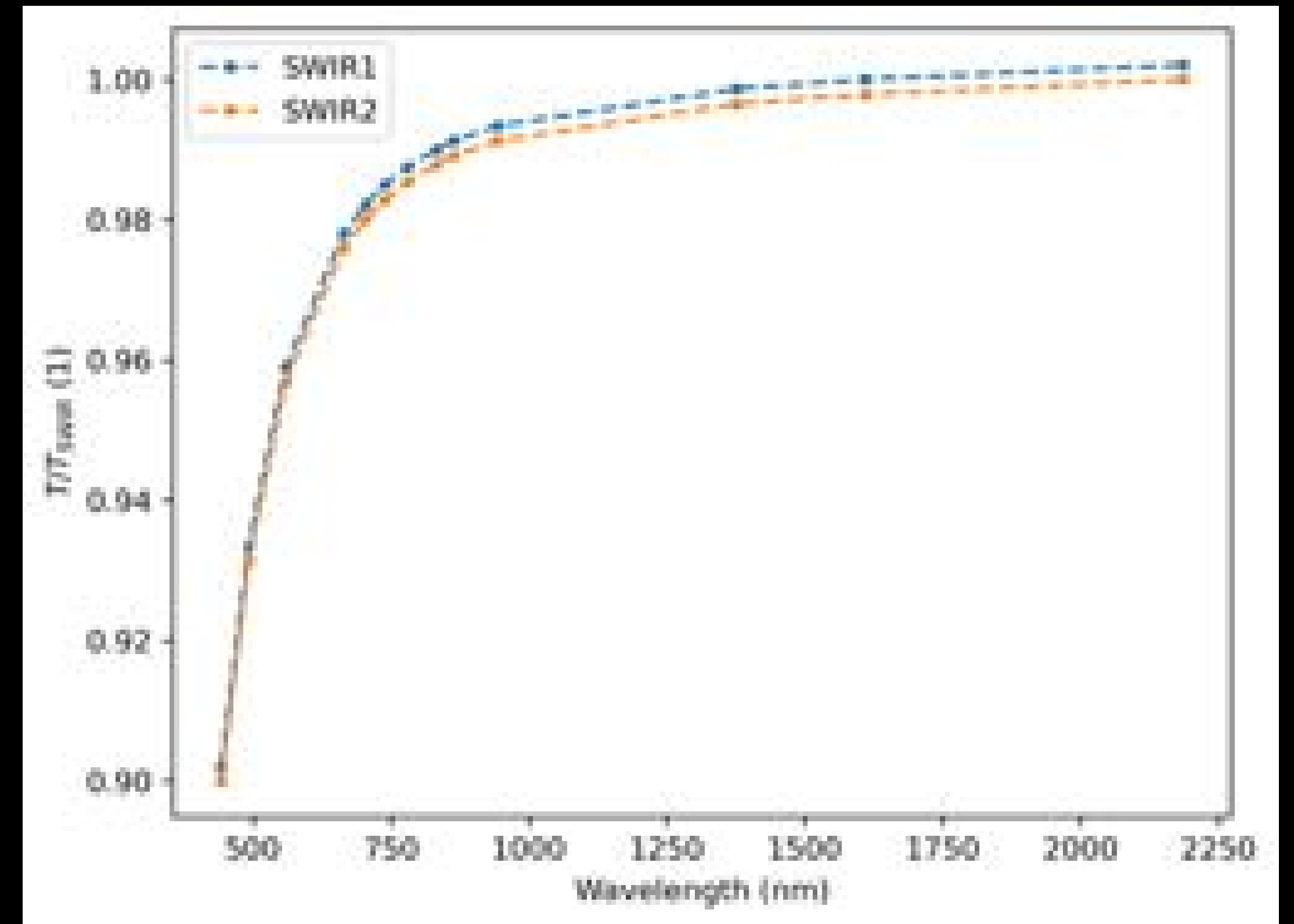
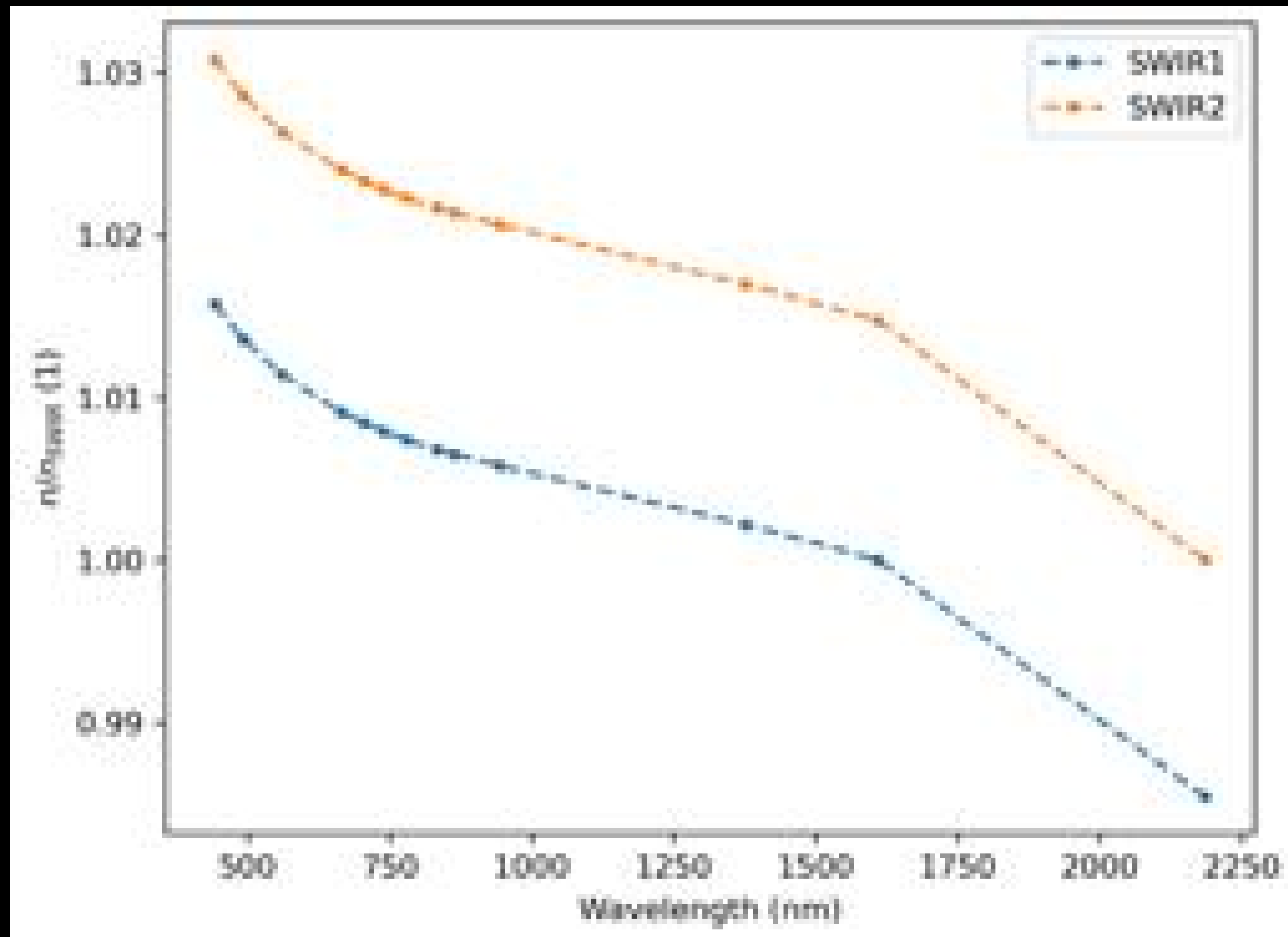
$$\rho_{glint} = \rho_{SWIR} \cdot \frac{n}{n_{SWIR}} \cdot \frac{T}{T_{SWIR}}$$



Harmel et al. (2018)

Glint correction

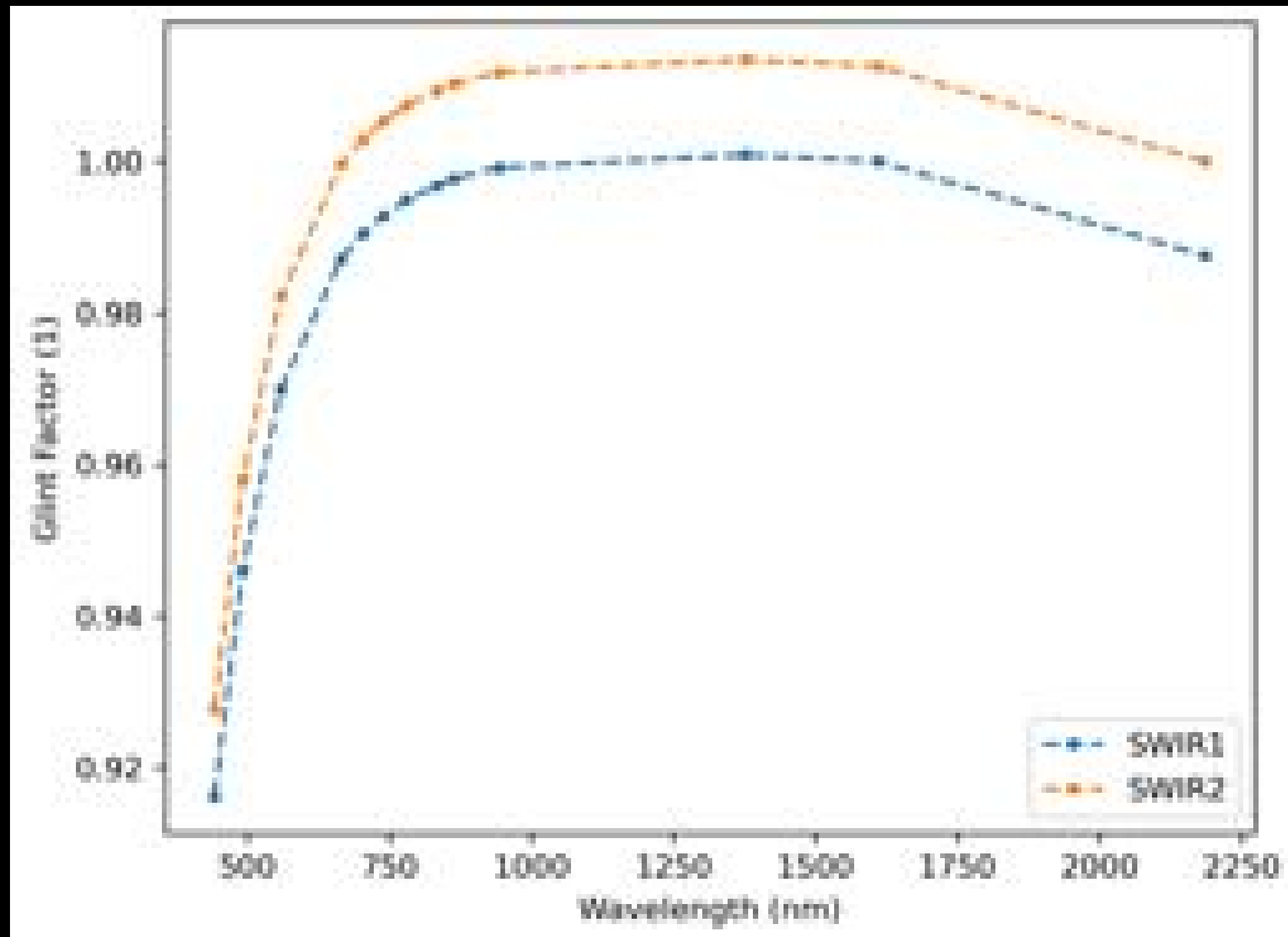
$$\rho_{glint} = \rho_{SWIR} \cdot \frac{n}{n_{SWIR}} \cdot \frac{T}{T_{SWIR}}$$



Harmel et al. (2018)

Glint correction

$$\rho_{glint} = \rho_{SWIR} \cdot \frac{n}{n_{SWIR}} \cdot \frac{T}{T_{SWIR}}$$



(ACOLITE: Choose SWIR band which gives lowest ρ_{glint} in Band 1)

Harmel et al. (2018)

Glint correction

SZA/MSI 2026-06-28 10:18:26
 ρ_s RGB

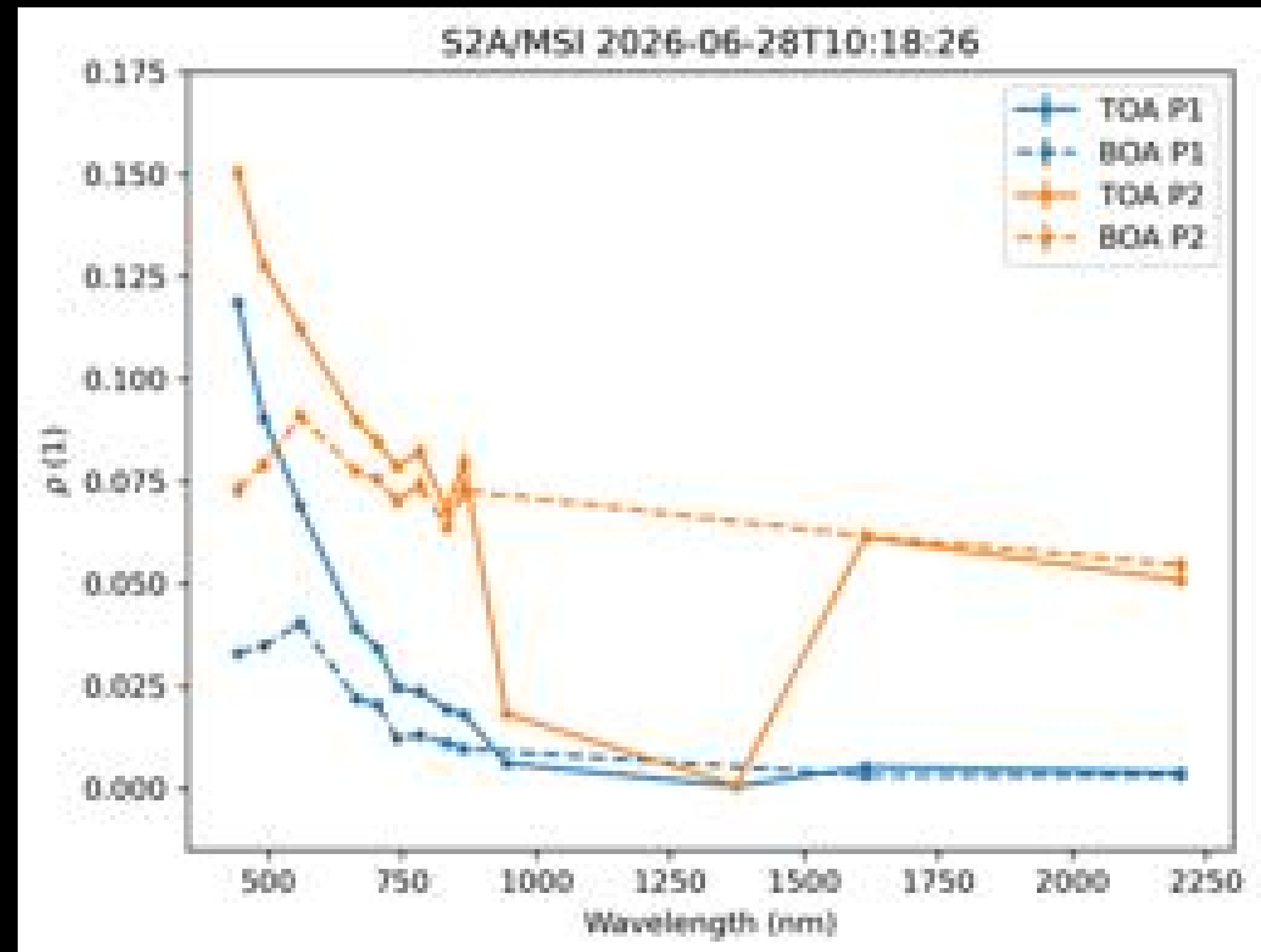


SZA/MSI 2026-06-28 10:18:26
 ρ_s RGB



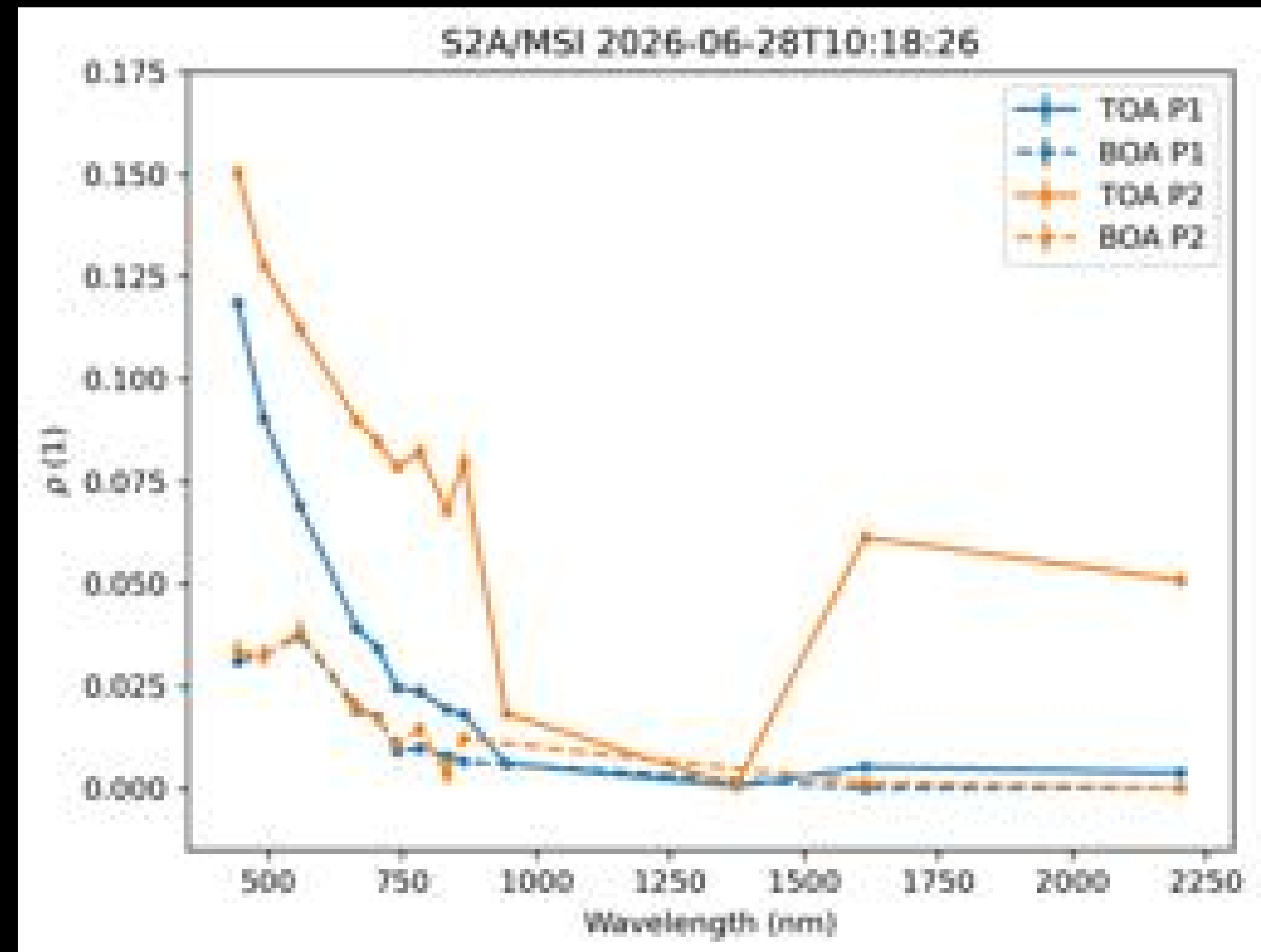
Glint correction

S2A/MSI 2026-06-28 10:18:26
 ρ_s RGB



Glint correction

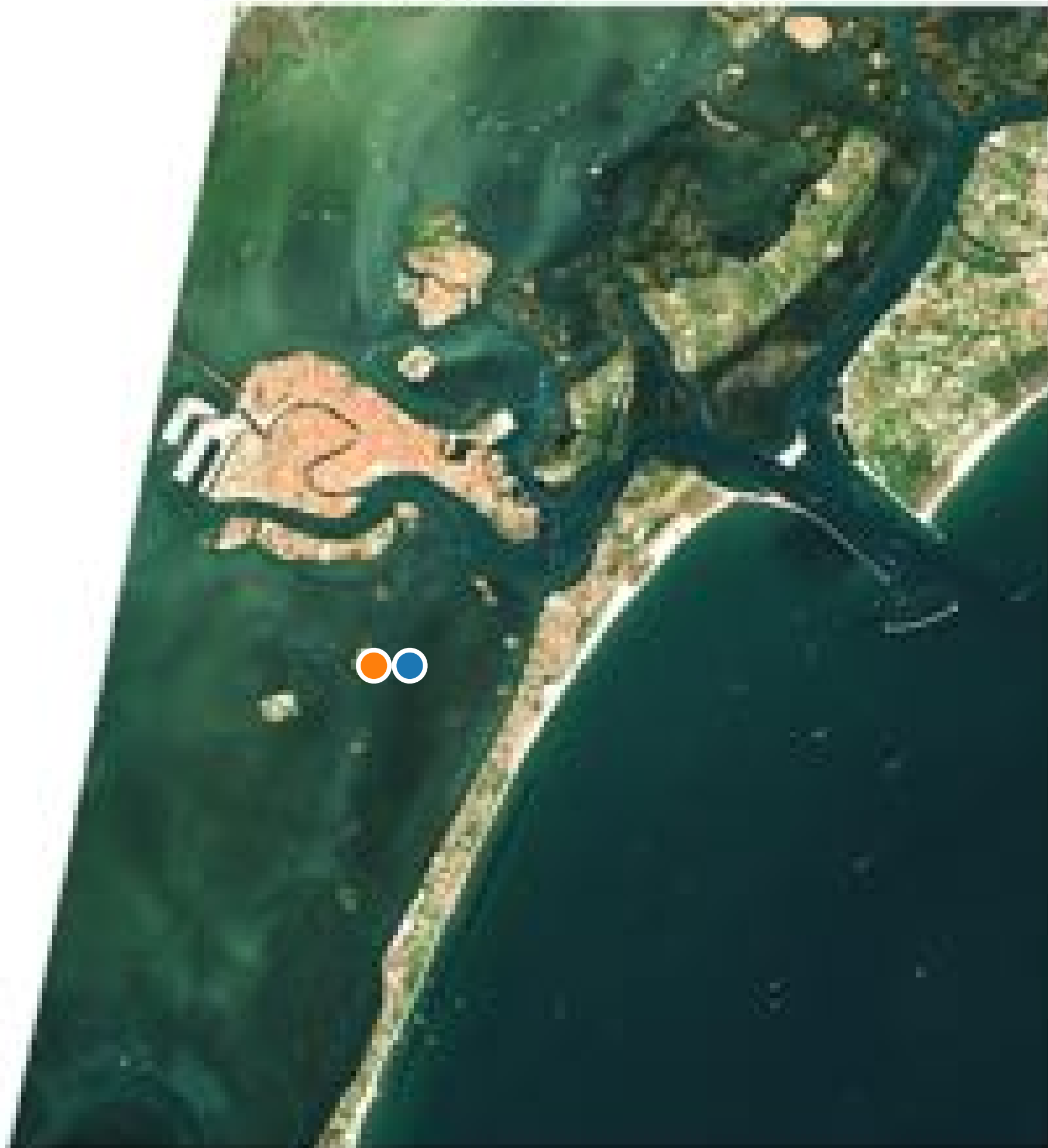
S2A/MSI 2026-06-28 10:18:26
 ρ_s RGB



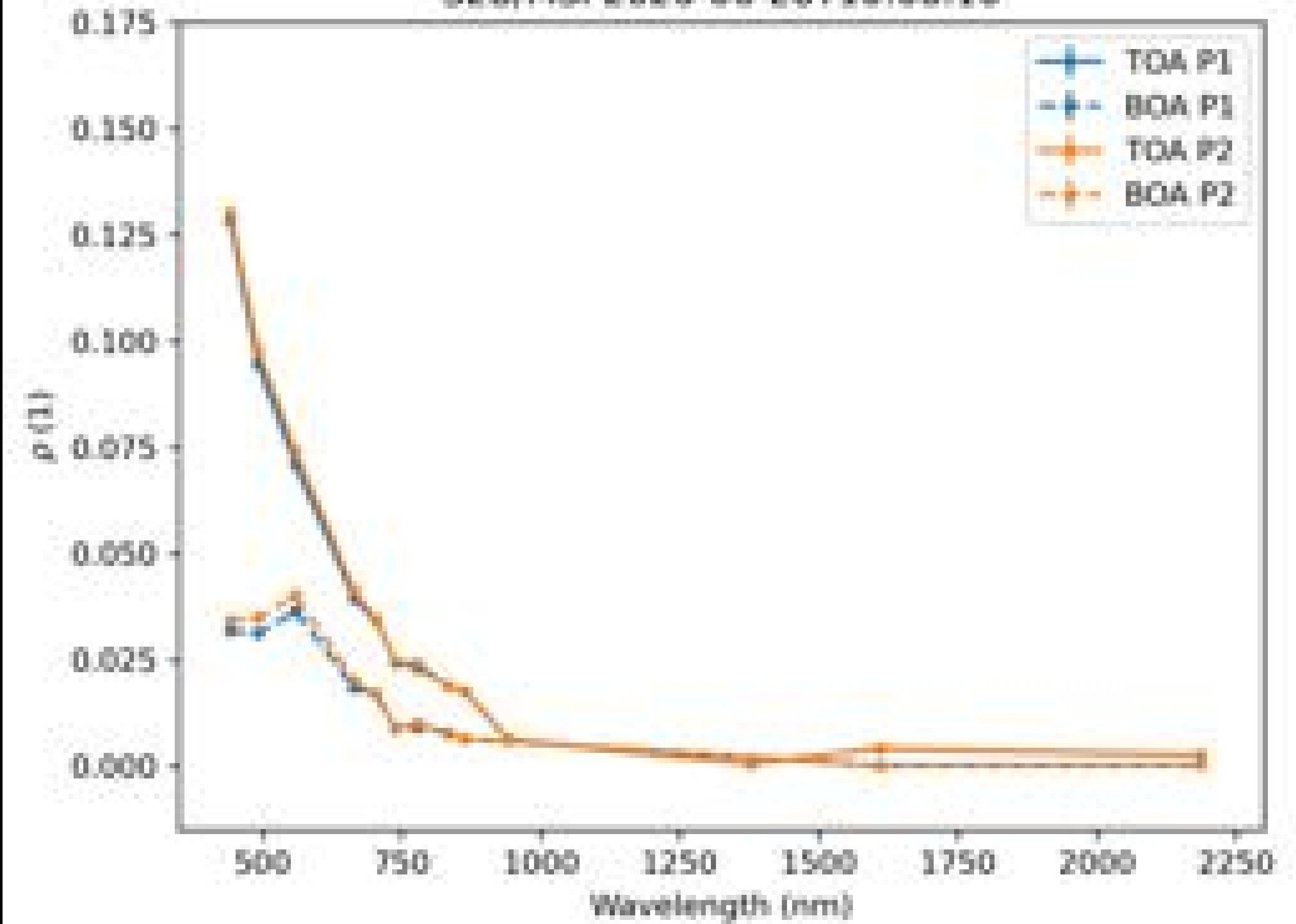
Glint correction

S2B/MSI 2026-06-28 10:08:10

ρ_s RGB



S2B/MSI 2026-06-28T10:08:10



Conclusions

Atmospheric correction over complex waters, is determined by conditions that invalidate algorithm assumptions.

Many algorithms struggle in the presence of high NIR ρ_t , for example high turbidity, glint, and adjacency effects, which invalidates assumptions or exceeds training/model range.

ACOLITE/DSF and RAdCor show fairly robust retrievals under conditions where other algorithms fail, but may perform worse for low reflectance waters.