Bio-optical and biogeochemical measurements in support of satellite ocean color calibration and validation

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During the 2011 ICESCAPE campaign, NASA's Goddard Space Flight Center (GFSC) group performed bio-optical measurements during 14 Arctic Survey Boat (ASB) deployments off the USCG cutter Healy (Fig. 1). During those deployments, 67 casts were performed for the measurement of apparent optical properties (AOPs), and 48 for the determination of inherent optical properties (IOPs; i.e., absorption and scattering) (Tables 1, 2). The group's work was focused around the ASB deployments due to the better suitability of this smaller platform, over the 420 ft cutter, for accurate measurements of the underwater light field. The ASB platform allowed the measurement of optical properties in the water column with its vertical physical structure nearly intact. Measurements were possible within the ubiquitous, near-surface low salinity melt-water layer that develops during the summer months.

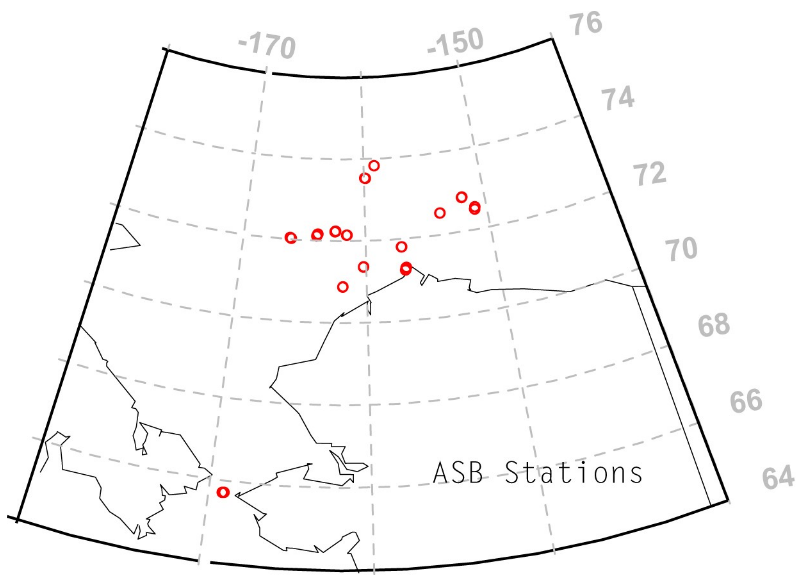

Figure 1. Locations of Arctic Survey Boat (ASB) deployments during the ICESCAPE 2011 campaign.

The bio-optical measurements were conducted to support calibration and validation activities for the current NASA ocean color satellite missions. The AOP measurements included in-water instruments (Submersible Biospherical Optical Profiling System, SuBOPS; Biospherical Instruments, Inc.) to determine spectral water-leaving radiances that are essential to remote sensing applications. The IOP measurements were centered on the HOBI Labs Inc. (Bellevue, WA) instrument package, which was modified to include an AC-9 absorption and attenuation meter from WETLabs Inc. (Philomath, OR). The HOBI Labs package comprises a Hydroscat-6 backscattering and fluorescence meter; an a-Sphere in-situ spectral absorption meter; a Seabird Electronics (Bellevue, WA)

FastCAT CTD sensor; and photosynthetically active radiation (PAR) sensors from Biospherical. Both systems used Biospherical reference radiometers to measure incident solar irradiance. AOP and IOP cast were conducted to maximum depths of 60 and 37 m, respectively.

At each of the ASB deployments where optical measurements were conducted, near-surface (< 50 cm) water was collected from the ASB for the analyses, at GFSC, of phytoplankton pigments using HPLC techniques (*n*=53), particulate organic carbon (POC) (*n*=36), gravimetric determination of suspended particulate matter (SPM) (*n*=21), dissolved organic carbon (DOC) (*n*=52), and light absorption by particulates (a_p) (*n*=36), and colored dissolved organic matter (a_{CDOM}) (*n*=52). These data, in conjunction with the concurrent bio-optical measurements, will be valuable for the development and further refinement of algorithms for the determination of phytoplankton pigments and other novel data products (e.g. DOC, POC) from remote sensing platforms.

One of our group's objectives is to further understanding of the quantitative relationships between AOPs and IOPs, and in turn with the dissolved and the suspended (living and detrital) components within the water column layer amenable to ocean color remote sensing detection. To that effect, during the current campaign we refined our IOP sampling design to differentiate from the bulk *in situ* absorption properties of the water column, those attributable to the dissolved and particulate fractions. During consecutive IOP casts at the same sampling location, a 0.2 μm filtering capsule was attached, alternatively, to the intake flow of the AC-9 and a-Sphere instruments. For each instrument, at each location, we measured then during one cast the absorption properties of the intact water column (i.e., "unfiltered"), and one where particles where excluded (i.e., "filtered") (Figures 2, 3).

Preliminary data from stations 152 and 166 (Figures 2-5) exemplify some of the challenges associated with the determination of phytoplankton pigments accurately from space. The fluorescence profiles at 700 nm (Figures 2a, 3a) suggest contrasting chlorophyll *a* stocks at these locations. At station 152 the fluorescence is flat and low throughout the profile relative to the values found at station 166, which exhibited a sharp fluorescence peak below 30 m depth (Figure 3a). At the latter site, an increase in backscattering was strongly associated with that high chlorophyll layer. At station 152, however, the high scattering layers were associated with a relatively negligible increase in the fluorescence signal (Figure 2a). The absorption profiles at each site, measured with both the a-Sphere and the AC-9 instruments, show overall agreement with backscattering values, where high absorption was found at layers with an elevated backscattering signal (Figures 2b, c, 3b, c). Absorption spectra for all depths (Figures 2d, e, 3d, e), and moreover, the particle absorption (a_p) profile estimated from the difference between the filtered and unfiltered casts (Figures 2f, g, 3f, g) provide additional evidence about the constituents imparting different optical properties to the water column at these two sites. The a_p spectra at station 152 shows the typical monotonic decrease from lower to higher wavelengths associated with absorption by chomophoric detrital material (Figure 2f, g). In contrast, the a_p spectra at station 166 is reminiscent to that of chlorophyll and associated phytoplankton pigments (3f, g).

The preliminary AOP data do not show these differences as clearly as the IOP data. While differences in the rate of attenuation of E_d are visible (figure 4a, 5a), the remote-sensing reflectances (R_{rs}, figures 4c, 5c) are remarkably similar, with a higher, broader peak in the green wavelengths at station 152, and a narrower, slightly bluer reflectance at station 166.

One of the objectives of the data analyses of the wider dataset yet to be conducted, including that from the previous year's mission, will be to better establish the quantitative relation between the optical parameters measured and the various components, living detrital, and dissolved. These data will allow us to expand the current understanding of the bio-optical variability in this high latitude environment, where climate record-quality measurements to support calibration and validation of ocean color missions are lacking.

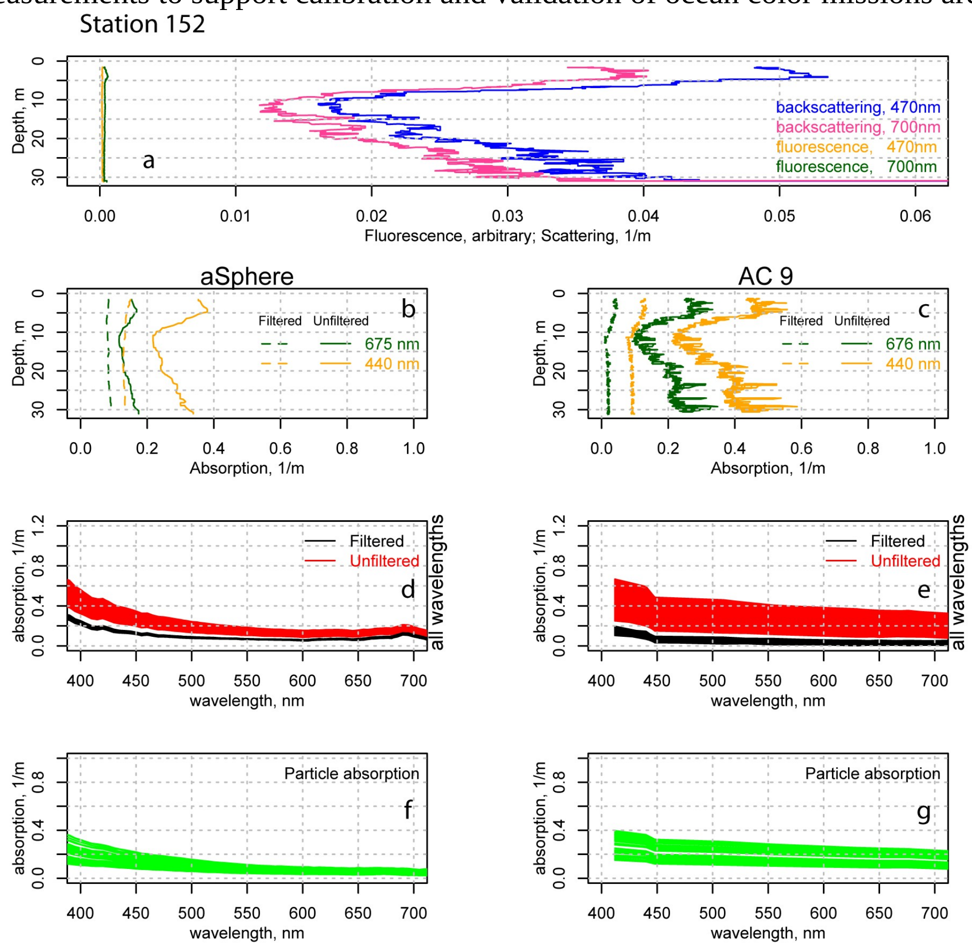

Figure 2. Station 152, ASB, July 22, 2011. a. Profiles of backscattering (b_b) and fluorescence at 470 nm and 700 nm. Profiles of absorption at 440 nm and 675 for filtered and unfiltered consecutive casts performed with the aSphere (b), and the AC-9 (c). Absorption (*a*) spectra for all depths for consecutive filtered and unfiltered casts performed with the aSphere (d), and the AC-9 (e),. Computed particle absorption (a_p) from the difference between binned absorption averages for filtered and unfiltered casts at 1.0 m depth bins, for the aSphere (f), and the AC-9 (g).

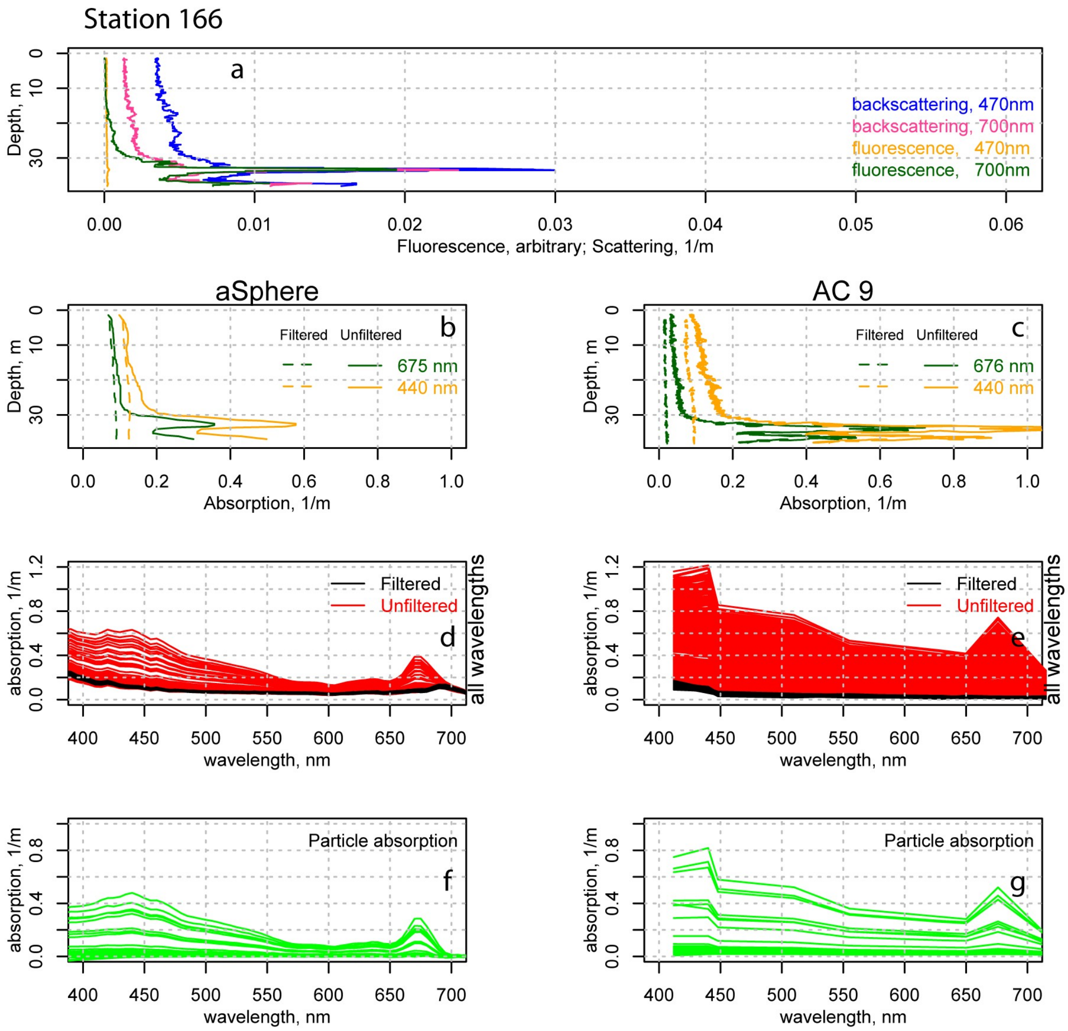

Figure 3. Station 166, ASB, July 23, 2011. a. Profiles of backscattering (b_b) and fluorescence at 470 nm and 700 nm. Profiles of absorption at 440 nm and 675 for filtered and unfiltered consecutive casts performed with the aSphere (b), and the AC-9 (c). Absorption (a) spectra for all depths for consecutive filtered and unfiltered casts performed with the aSphere (d), and the AC-9 (e),. Computed particle absorption (a_p) from the difference between binned absorption averages for filtered and unfiltered casts at 1.0 m depth bins, for the aSphere (f), and the AC-9 (g).

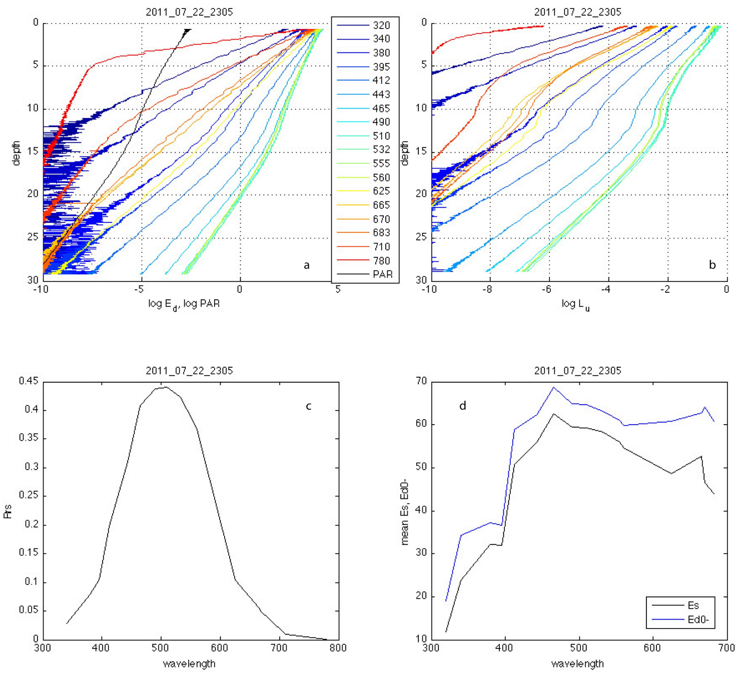

Figure 4. Station 152, ASB, July 22, 2011. A. E_d and PAR vs depth. B. L_u vs depth. C. R_{rs} D. E_d and mean E_s

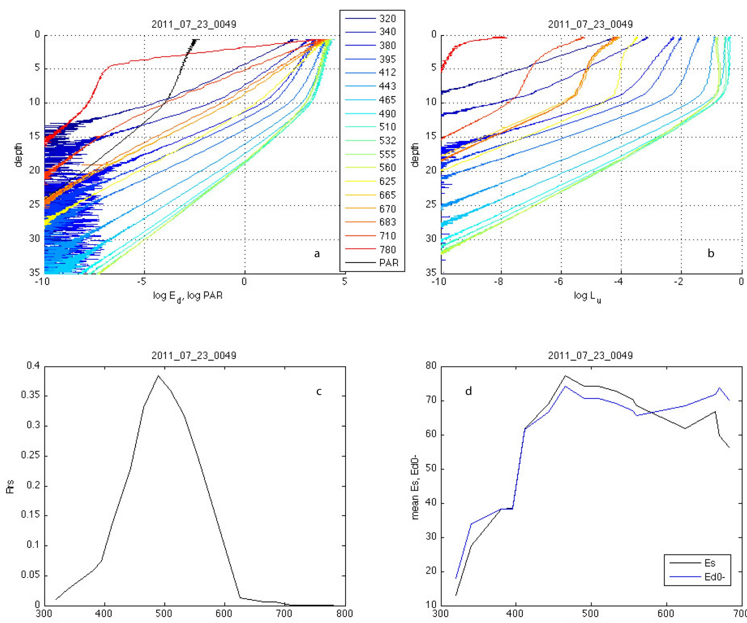

Figure 5: Station 166, ASB, July 23, 2011. A. E_d and PAR vs depth. B. L_u vs depth. C. R_{rs} D. E_d and mean E_s

Table 1. The AOP Master Log for USCG Healy 2011 field campaign with all times in GMT. Longitude and latitude are given in decimal degrees, depths in meters.

File	Longitude	Latitude	station	Depth (m)	Sky Conditions	wind speed (kn)
2011_06_28_2146	-168.776	65.724	8	55	8/8 overcast	21
2011_06_28_2149	-168.776	65.724	8	55	8/8 overcast	21
2011_06_28_2152	-168.773	65.724	8	55	8/8 overcast	21
2011_06_28_2321	-168.900	65.718	8	55	8/8 overcast	21
2011_06_28_2325	-168.900	65.718	8	55	8/8 overcast, light rain	21
2011_06_28_2328	-168.900	65.717	8	55	8/8 overcast	21
2011_07_02_2213	-161.794	70.886	31	50	8/8 overcast	11
2011_07_02_2217	-161.795	70.885	31	50	8/8 overcast	11
2011_07_02_2220	-161.795	70.885	31	50	8/8 overcast	11
2011_07_02_2336	-161.790	70.888	31	50	6/8 overcast, lt rain	11
2011_07_02_2339	-161.790	70.887	31	50	4/8 overcast	11
2011_07_02_2344	-161.790	70.887	31	50	2/8 overcast	11
2011_07_02_2351	-161.788	70.887	31	50	2/8 overcast	11
2011_07_03_2258	-165.874	72.024	46	48	8/8 overcast	20
2011_07_03_2302	-165.878	72.024	46	48	8/8 overcast	20
2011_07_03_2308	-165.884	72.024	46	48	8/8 overcast	20
2011_07_04_0026	-165.959	72.041	46	48	8/8 overcast	20
2011_07_04_0029	-165.961	72.042	46	48	8/8 overcast	20
2011_07_04_0034	-165.966	72.042	46	48	8/8 overcast	20
2011_07_08_2202	-163.780	72.168	73	50	0/8 bright sun	14
2011_07_08_2212	-163.787	72.167	73	50	0/8 bright sun	14
2011_07_08_2217	-163.790	72.166	73	50	0/8 bright sun	14
2011_07_08_2357	-163.852	72.131	73	50	0/8 bright sun	14
2011_07_09_0001	-163.855	72.130	73	50	0/8 bright sun	14
2011_07_09_0005	-163.858	72.130	73	50	0/8 bright sun	14
2011_07_09_2145	-162.339	72.246	81	38	2/8 fog/haze	18
2011_07_09_2152	-162.346	72.246	81	38	2/8 fog/haze	18
2011_07_09_2202	-162.356	72.246	81	38	2/8 fog/haze	18
2011_07_09_2317	-162.368	72.237	81	39	6/8 clouds, no haze	17
2011_07_09_2322	-162.373	72.237	81	39	6/8 clouds, no haze	17
2011_07_09_2327	-162.377	72.237	81	39	6/8 clouds, no haze	17
2011_07_12_0031	-159.822	73.524	99	2017	8/8 overcast	13
2011_07_12_0042	-159.837	73.525	99	2017	8/8 overcast	13
2011_07_12_0050	-159.849	73.527	99	2017	8/8 overcast	13
2011_07_13_2157	-159.047	73.831	101	3169	1/8 clouds on horizon	11
2011_07_13_2204	-159.052	73.831	101	3169	1/8 clouds on horizon	11
2011_07_13_2209	-159.055	73.831	101	3169	1/8 clouds on horizon	11
2011_07_13_2221	-159.049	73.832	101	3169	1/8 clouds on horizon	11
2011_07_15_2258	-161.408	72.152	113	35	4/8 high clouds	18
2011_07_15_2303	-161.413	72.152	113	35	4/8 high clouds	18
2011_07_15_2312	-161.424	72.153	113	35	4/8 high clouds	18
2011_07_16_2323	-157.137	71.812	126	70	3/8 thin high clouds	16
2011_07_16_2329	-157.144	71.811	126	70	3/8 thin high clouds	16
2011_07_16_2339	-157.155	71.811	126	70	3/8 thin high clouds	16

2011_07_16_2344	-157.160	71.811	126	70	3/8 thin high clouds	16
2011_07_18_0204	-153.812	72.539	127	3060	3/8 thin high clouds	9
2011_07_18_0210	-153.816	72.539	127	3060	3/8, then fog, 8/8	9
2011_07_18_0218	-153.822	72.538	127	3060	8/8 fog	9
2011_07_18_2244	-151.870	72.843	128	3817	3/8 fog and sun	4
2011_07_18_2250	-151.868	72.843	128	3817	3/8 fog and sun	4
2011_07_18_2257	-151.865	72.842	128	3817	3/8 fog and sun	4
2011_07_19_0014	-151.913	72.831	128	3817	6/8 fog and sun	7
2011_07_19_0020	-151.910	72.831	128	3817	6/8 fog and sun	7
2011_07_19_0027	-151.910	72.831	128	3817	6/8 fog and sun	7
2011_07_19_0030	-151.909	72.831	128	3817	6/8 fog and sun	7
2011_07_20_2105	-150.950	72.486	133	3622	7/8 thick clouds	20
2011_07_20_2115	-150.955	72.488	133	3622	7/8 thick clouds	20
2011_07_20_2124	-150.959	72.489	133	3622	7/8 thick clouds	20
2011_07_20_2254	-150.973	72.494	133	3622	7/8 thick clouds	18
2011_07_20_2300	-150.925	72.545	133	3622	7/8 thick clouds	18
2011_07_20_2308	-150.928	72.546	133	3622	7/8 thick clouds	18
2011_07_22_2257	-157.048	71.229	152	35	8/8 thick and thin clouds	6
2011_07_22_2305	-157.041	71.231	152	35	8/8 thick and thin clouds	6
2011_07_22_2310	-157.037	71.232	152	35	8/8 thick and thin clouds	6
2011_07_23_0039	-156.987	71.292	152	45	8/8 thick and thin clouds	6
2011_07_23_0044	-156.982	71.293	152	45	8/8 thick and thin clouds	6
2011_07_23_0049	-156.977	71.294	152	45	8/8 thick and thin clouds	6
2011_07_23_2302	-160.196	71.376	166	46	8/8 fog and clouds, disc present	5
2011_07_23_2310	-160.196	71.375	166	46	8/8 fog and clouds, disc present	5
2011_07_23_2318	-160.196	71.375	166	46	8/8 fog and clouds, disc present	5

Table 2. The IOP Master Log for USCG Healy 2011 field campaign with all times in GMT. Longitude and latitude are given in decimal degrees, depths in meters.

Cast	Date	BegCast	EndCast	Latitude	Longitude	Cast z	filtration	UpDown	Station	Bottom z
101	28Jun11	2221	2224	65.7207	-168.7859	14	no	D	8	55
101	28Jun11	2224	2227	65.7206	-168.7847	14	no	U	8	55
102	28Jun11	2358	0004	65.7146	-168.8979	20	no	D	8	55
102	29Jun11	0004	0007	65.7137	-168.8992	20	no	U	8	55
103	2Jul11	2247	2250	70.8824	-161.8029	20	no	D	31	50
103	2Jul11	2250	2252	70.8819	-161.8039	20	no	U	31	50
104	2Jul11	2308	2314	70.8898	-161.7861	20	no	D	31	50
104	2Jul11	2314	2317	70.8891	-161.7874	20	no	U	31	50
105	3Jul11	2340	2344	72.0283	-165.9035	26	no	D	46	48
105	3Jul11	2344	2348	72.0287	-165.9102	26	no	U	46	48
106	4Jul11	2358	0003	72.0291	-165.9189	26	yes	D	46	48
106	4Jul11	0003	0008	72.0294	-165.9267	26	yes	U	46	48
108	4Jul11	0106	0111	72.0461	-165.9903	31	yes	D	46	48
108	4Jul11	0111	0117	72.0472	-165.9976	31	yes	U	46	48
109	4Jul11	0122	0128	72.0478	-166.0018	33	no	D	46	48
109	4Jul11	0128	0134	72.0485	-166.0089	33	no	U	46	48
110	8Jul11	2257	2305	72.1670	-163.8029	37	no	D	73	50
110	8Jul11	2305	2314	72.1654	-163.8132	37	no	U	73	50
111	8Jul11	2327	2336	72.1633	-163.8225	35	yes	D	73	50
111	8Jul11	2336	2343	72.1608	-163.8318	35	yes	U	73	50
112	9Jul11	0028	0034	72.1246	-163.8741	31	yes	D	73	50
112	9Jul11	0034	0041	72.1219	-163.8831	31	yes	U	73	50
113	9Jul11	0046	0052	72.1206	-163.8870	31	no	D	73	50
113	9Jul11	0052	0058	72.1182	-163.8949	31	no	U	73	50
114	9Jul11	2224	2232	72.2461	-162.3789	34	no	D	81	38
114	9Jul11	2232	2239	72.2458	-162.3926	34	no	U	81	38
115	9Jul11	2246	2255	72.2457	-162.3995	34	yes	D	81	38
115	9Jul11	2255	2302	72.2452	-162.4143	34	yes	U	81	38
116	9Jul11	2345	2351	72.2353	-162.3925	35	yes	D	81	38
116	9Jul11	2351	2357	72.2346	-162.4019	35	yes	U	81	38
118	10Jul11	0027	0032	72.2320	-162.4259	35	yes	D	81	38
118	10Jul11	0032	0037	72.2313	-162.4334	35	yes	U	81	38
119	10Jul11	0043	0050	72.2315	-162.4315	34	no	D	81	38
119	10Jul11	0050	0056	72.2307	-162.4421	34	no	U	81	38
120	12Jul11	0113	0119	73.5298	-159.8599	32	no	D	99	2000
120	12Jul11	0119	0124	73.5311	-159.8746	32	no	U	99	2000
121	12Jul11	0128	0135	73.5319	-159.8793	34	yes	D	99	2000
121	12Jul11	0135	0143	73.5334	-159.8992	34	yes	U	99	2000
122	12Jul11	0200	0206	73.5367	-159.9245	35	yes	D	99	2000
122	12Jul11	0206	0212	73.5374	-159.9301	35	yes	U	99	2000
123	13Jul11	2240	2247	73.8319	-159.0563	37	no	D	101	3169
123	13Jul11	2247	2252	73.8320	-159.0639	37	no	U	101	3169
124	13Jul11	2300	2305	73.8323	-159.0614	37	yes	D	101	3169
124	13Jul11	2305	2311	73.8323	-159.0646	37	yes	U	101	3169
125	13Jul11	2320	2324	73.8329	-159.0683	37	yes	D	101	3169
125	13Jul11	2324	2330	73.8333	-159.0738	37	yes	U	101	3169

126	15Jul11	2343	2350	72.1502	-161.4627	30	no	D	113	35
126	15Jul11	2350	2354	72.1495	-161.4729	30	no	U	113	35
127	16Jul11	0004	0010	72.1508	-161.4825	30	yes	D	113	35
127	16Jul11	0010	0014	72.1499	-161.4919	30	yes	U	113	35
128	16Jul11	0021	0027	72.1498	-161.4987	30	yes	D	113	35
128	16Jul11	0027	0033	72.1495	-161.5101	30	yes	U	113	35
129	17Jul11	0011	0017	71.8115	-157.1606	29	no	D	126	70
129	17Jul11	0017	0022	71.8109	-157.1714	29	no	U	126	70
130	17Jul11	0028	0032	71.8108	-157.1769	31	yes	D	126	70
130	17Jul11	0032	0039	71.8100	-157.1857	31	yes	U	126	70
131	17Jul11	0048	0054	71.8115	-157.1855	29	yes	D	126	70
131	17Jul11	0054	0101	71.8105	-157.1962	29	yes	U	126	70
132	18Jul11	0309	0314	72.5344	-153.8275	37	no	D	127	3060
132	18Jul11	0314	0320	72.5338	-153.8348	37	no	U	127	3060
133	18Jul11	0327	0333	72.5333	-153.8402	37	yes	D	127	3060
133	18Jul11	0333	0340	72.5326	-153.8483	37	yes	U	127	3060
134	18Jul11	0350	0356	72.5338	-153.8462	37	yes	D	127	3060
134	18Jul11	0356	0402	72.5330	-153.8540	37	yes	U	127	3060
135	18Jul11	2322	2328	72.8415	-151.8588	37	yes	D	128	3817
135	18Jul11	2328	2335	72.8408	-151.8538	37	yes	U	128	3817
136	18Jul11	2340	2346	72.8404	-151.8520	37	yes	D	128	3817
136	18Jul11	2346	2352	72.8399	-151.8479	37	yes	U	128	3817
137	19Jul11	0051	0056	72.8300	-151.9007	37	yes	D	128	3817
137	19Jul11	0056	0103	72.8295	-151.8962	37	yes	U	128	3817
138	19Jul11	0108	0113	72.8290	-151.8938	37	yes	D	128	3817
138	19Jul11	0113	0122	72.8284	-151.8893	37	yes	U	128	3817
139	20Jul11	2154	2200	72.4939	-150.9731	37	yes	D	133	3622
139	20Jul11	2200	2207	72.4960	-150.9799	37	yes	U	133	3622
140	20Jul11	2224	2232	72.4994	-150.9936	37	yes	U	133	3622
141	20Jul11	2333	2339	72.5486	-150.9294	37	yes	D	133	3622
141	20Jul11	2339	2344	72.5494	-150.9337	37	yes	U	133	3622
142	20Jul11	2349	2356	72.5498	-150.9355	37	yes	D	133	3622
142	21Jul11	2356	0003	72.5506	-150.9380	37	yes	U	133	3622
143	21Jul11	0009	0015	72.5508	-150.9394	37	no	D	133	3622
143	21Jul11	0015	0020	72.5512	-150.9432	37	no	U	133	3622
145	22Jul11	2336	2343	71.2392	-157.0088	30	yes	D	152	35
145	22Jul11	2343	2350	71.2428	-156.9963	30	yes	U	152	35
146	22Jul11	2357	0004	71.2446	-156.9888	30	yes	D	152	35
146	23Jul11	0004	0011	71.2479	-156.9752	30	yes	U	152	35
147	23Jul11	0105	0112	71.2961	-156.9609	37	yes	D	152	48
147	23Jul11	0112	0118	71.2986	-156.9491	37	yes	U	152	48
148	23Jul11	0135	0142	71.3020	-156.9310	37	yes	D	152	48
148	23Jul11	0142	0148	71.3043	-156.9204	37	yes	U	152	48
149	23Jul11	2339	2348	71.3729	-160.2005	37	yes	D	166	49
149	23Jul11	2348	2355	71.3710	-160.2034	37	yes	U	166	49
150	24Jul11	0006	0012	71.3690	-160.2050	37	yes	D	166	49
150	24Jul11	0012	0018	71.3674	-160.2074	37	yes	U	166	49
153	24Jul11	0036	0038	71.3649	-160.2119	37	yes	D	166	49
153	24Jul11	0038	0045	71.3635	-160.2149	37	yes	U	166	49