Reflectivity report: analysis of measurements on WHT primary mirror, before and after CO2 cleaning on **Weds 15th March.**

6 weeks since last measurement and 9 weeks since last cleaning (CO2 N48). Cleaning, measurement and report by Neil O'Mahony

Headline: fresh CO2 bottle improved scattering 0.5% and restored refelctivity to levels obtained after December cleaning.

Cleaning was prompted by dusty calima weather 21-24 Feb (max. 85 g/m3) and again 2-11 March (max.36 ug/m3)
Cleaning was carried out using N48 CO2 (new bottle) for ~8 minutes **followed by Aligal2** (all except top of mirror) for 2-3 minutes.
Aligal flakes were very small but were observed to stick slightly to the mirror. **RH% 20%, Dome Temp. 6 degC, dewpoint -16 degC**.

At least 16 samples were taken to reduce statistical uncertainties affecting previous 2 reports.
Only CT7 data taken. Best values (max. %R and min. %DI) highlighted in green. Worst in red.

				Tempr. °C	Reflectivity % wavelength of band (nm)							"Dust Indices" (model % scattering) per waveband						
Before cleaning.			position		365	404	464	522	624	760	970	365	404	464	522	624	760	970
1014	13/03/2017 10:21	1	left	18.5	87.7	86.3	85.9	85.7	84.9	82.2	87.6	7.9	8.4	9.5	8.2	9.9	9.6	10.4
1015	13/03/2017 10:21	1	left	18.5	88.5	87.2	86.7	86.7	85.6	83.0	88.7	7.3	7.5	8.4	7.2	8.7	8.2	8.8
1016	13/03/2017 10:23	1	left	18.5	89.2	87.6	87.1	87.0	86.3	83.3	89.3	6.7	7.0	7.7	6.4	7.6	7.3	7.6
1017	13/03/2017 10:24	1	top	18.5	88.7	86.8	86.5	85.8	85.8	82.4	88.8	7.5	7.6	8.2	7.1	8.3	7.9	8.2
1018	13/03/2017 10:25	1	top	18.6	88.6	87.3	86.8	86.9	85.9	83.3	88.9	7.7	7.4	8.3	6.8	8.2	7.4	7.9
1019	13/03/2017 10:26	1	top	18.6	88.8	87.3	86.9	87.0	86.0	83.4	89.0	7.1	7.2	7.5	6.3	7.6	7.0	7.6
1020	13/03/2017 10:26	1	top	18.6	88.9	87.4	86.9	87.1	86.2	83.5	89.1	6.7	6.7	7.4	6.2	7.4	6.9	7.5
1021	13/03/2017 10:27	1	right	18.7	88.4	86.8	86.2	86.1	85.2	82.3	87.9	7.4	7.9	8.9	7.7	9.3	9.0	9.8
1022	13/03/2017 10:28	1	right	18.8	88.8	87.4	87.0	87.0	86.1	83.4	89.0	7.0	6.7	7.2	6.2	7.5	6.8	7.5
1023	13/03/2017 10:29	1	right	18.8	88.8	87.3	86.9	86.9	85.9	83.3	88.7	7.0	6.9	7.7	6.7	8.1	7.4	8.2
1024	13/03/2017 10:30	1	right	18.8	88.9	87.4	86.8	86.9	85.9	83.1	89.0	6.8	6.9	7.8	6.5	8.0	7.3	7.8
1025	13/03/2017 10:31	1	right	18.8	87.7	86.1	85.5	85.5	84.5	81.6	87.2	7.9	8.2	9.5	8.4	10.4	10.0	10.7
1026	13/03/2017 10:32	1	bottom	18.8	88.9	87.5	87.0	87.2	86.2	83.4	89.1	6.8	6.8	7.5	6.1	7.5	6.8	7.4
1027	13/03/2017 10:33	1	bottom	18.8	87.5	86.0	85.3	85.2	84.2	81.2	87.2	8.3	8.7	9.8	8.7	10.8	10.3	11.0
1028	13/03/2017 10:34	1	bottom	18.8	87.4	85.9	85.3	85.3	84.3	81.4	86.9	8.5	8.7	10.0	8.6	10.5	10.2	11.0
1029	13/03/2017 10:35	1	bottom	18.8	88.6	87.2	86.7	86.7	85.6	82.9	88.6	7.0	7.0	7.9	6.7	8.5	7.8	8.3
1030	13/03/2017 11:10	1	invalid	18.6	5.7	9.0	15.7	10.2	19.7	26.5	10.5	30.8	43.5	50.4	33.9	26.7	22.2	25.1
global averages					88.5	87.0	86.5	86.4	85.5	82.7	88.4	7.4	7.5	8.3	7.1	8.6	8.1	8.7

Minima			87.4	85.9	85.3	85.2	84.2	81.2	86.9	6.7	6.7	7.2	6.1	7.4	6.8	7.4
Maxima			89.2	87.6	87.1	87.2	86.3	83.5	89.3	8.5	8.7	10.0	8.7	10.8	10.3	11.0
			wavelength of band (nm)							"Dust Indices"						
Statistics of dusty mirror, Continued			365	404	464	522	624	760	970	365	404	464	522	624	760	970
range			1.8	1.7	1.8	2.0	2.1	2.3	2.4	1.8	2.0	2.8	2.6	3.4	3.5	3.6
std.deviation			0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.6	0.7	0.9	0.9	1.2	1.3	1.4
Average after CO2 cleaning 9/1/2017			90.2	88.8	88.3	88.4	87.5	84.8	91.0	6.4	6.1	6.6	5.2	6.1	5.4	5.5
Change in averages over 2 months			-1.7	-1.8	-1.8	-2.0	-2.0	-2.1	-2.6	0.9	1.4	1.8	1.9	2.6	2.7	3.2

Comment: significant dust has accumulated, reducing reflectivity increasingly toward the red, by about 2%, averaged across wavebands.

The standard error on the mean values is **larger than** (about twice) instrumental error, which is typical in a dusty mirror.

Reference mirror measurements																
1031	13/03/2017 11:11	0 Gauge	18.8	84.4	83.6	88.4	90.5	89.5	83.2	86.8	2.7	3.3	2.8	1.7	1.3	1.1	1.3
1032	13/03/2017 11:12	0 Gauge	19.0	84.4	83.8	88.6	90.7	89.5	83.3	86.9	2.7	3.6	2.6	1.5	1.2	0.9	1.2
1033	13/03/2017 11:13	0 Gauge	19.3	84.3	83.6	88.3	90.5	89.4	83.3	86.7	2.9	3.5	2.9	1.8	1.4	1.0	1.3
	direction of change (w.r.t. older)			low				low	low	low?							
Older reference measurements																	
956	30/01/2017 13:41	0 Gauge	21.4	84.6	83.8	88.6	90.7	89.7	83.5	87.1	2.6	3.2	2.4	1.4	1.1	0.8	1.0
918	07/12/2016 12:25	1 Gauge	12.1	84.5	83.6	88.4	90.6	89.6	83.4	86.7	2.7	3.2	2.8	1.7	1.3	1.0	1.2
Maximum discrepancy				0.3	0.2	0.3	0.2	0.3	0.3	0.4	0.3	0.4	0.5	0.4	0.3	0.3	0.3

Conclusion: Some reference values have decreased 0.3% since Januaury. Need to repeat ref. to confirm there has been no increase between 13th and 15th

Measurements after CO2 cleaning, Weds 15 March																
1034	15/03/2017 14:36	1 left	19.8	90.5	89.1	88.7	88.8	88.1	85.4	91.6	5.9	5.7	6.0	5.1	5.2	4.8	4.8
1035	15/03/2017 14:37	1 left	19.8	91.2	89.8	89.4	89.5	88.6	86.0	92.4	5.2	5.0	4.9	3.7	4.3	3.4	3.3
1036	15/03/2017 14:37	1 left	19.8	90.7	89.2	88.9	88.9	88.1	85.5	91.6	5.5	5.3	5.4	4.4	4.9	4.1	4.6
1037	15/03/2017 14:38	1 left	19.9	90.2	88.7	88.2	88.4	87.4	84.8	91.0	6.3	6.2	6.6	5.3	6.4	5.5	5.8
1038	15/03/2017 14:39	1 top	19.9	91.0	89.6	89.3	89.4	88.6	86.1	92.2	5.9	5.4	5.2	4.3	4.4	3.4	3.7
1039	15/03/2017 14:40	1 top	19.9	91.1	89.7	89.3	89.5	88.7	86.1	92.4	5.5	5.0	5.0	3.7	4.0	3.1	3.0
1040	15/03/2017 14:41	1 top	19.9	91.1	89.6	89.2	89.5	88.7	86.0	92.3	5.3	5.0	5.1	3.8	4.0	3.3	3.1
1041	15/03/2017 14:42	1 top	19.9	90.8	89.4	89.1	89.2	88.5	85.8	92.0	5.7	5.3	5.2	4.1	4.2	3.5	3.5
1042	15/03/2017 14:42	1 right	19.9	91.2	90.0	89.5	89.7	88.8	86.1	92.3	4.8	4.4	4.4	3.3	3.6	2.9	2.9

1043	15/03/2017 14:43	1	right	19.9	91.0	89.6	89.2	89.3	88.5	85.8	91.9	5.2	5.0	5.2	4.0	4.3	3.6	3.8
1044	15/03/2017 14:44	1	right	19.8	91.0	89.7	89.3	89.4	88.6	85.9	92.0	5.3	4.9	4.8	3.7	4.1	3.3	3.4
1045	15/03/2017 14:45	1	right	19.8	91.4	90.0	89.6	89.7	88.8	86.1	92.3	4.9	4.6	4.5	3.4	3.7	3.0	3.0
1046	15/03/2017 14:46	1	bottom	19.8	91.1	89.6	89.2	89.3	88.5	85.8	92.1	5.9	5.4	5.3	4.5	4.5	3.8	4.0
1047	15/03/2017 14:47	1	bottom	19.7	91.1	89.7	89.3	89.5	88.6	86.0	92.2	5.2	4.8	4.9	3.5	4.0	3.1	3.0
1048	15/03/2017 14:48	1	bottom	19.7	90.8	89.4	89.0	89.2	88.2	85.6	91.8	5.7	5.2	5.4	4.1	4.8	3.8	3.8
1049	15/03/2017 14:49	1	bottom	19.6	91.1	89.7	89.2	89.5	88.6	86.0	91.9	5.4	4.9	5.1	3.7	4.1	3.3	3.3
	averages per waveband				91.0	89.6	89.2	89.3	88.5	85.8	92.0	5.5	5.1	5.2	4.0	4.4	3.6	3.7
	Minima				90.2	88.7	88.2	88.4	87.4	84.8	91.0	4.8	4.4	4.4	3.3	3.6	2.9	2.9
	maxima				91.4	90.0	89.6	89.7	88.8	86.1	92.4	6.3	6.2	6.6	5.3	6.4	5.5	5.8
	ranges				1.2	1.3	1.4	1.3	1.4	1.3	1.4	1.5	1.8	2.2	2.0	2.8	2.6	2.9
	std.deviation				0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.7	0.7	0.8
	std. error				0.07	0.08	0.08	0.08	0.09	0.09	0.09	0.11	0.11	0.13	0.13	0.18	0.17	0.19

Note: After CO2, std. error σ/√N < 0.1, about the size of estimated instrumental error or typical variations in Reference (gauge) measurements.

	deviation of minimum from next	0.3	0.4	0.5	0.4	0.7	0.6	0.6	0.4	0.5	0.6	0.2	1.2	0.7	1.0
	averages omitting minimum	91.0	89.6	89.2	89.4	88.5	85.9	92.1	5.4	5.1	5.1	4.0	4.3	3.5	3.5
	ranges omitting minimum	0.9	0.9	0.9	0.9	0.7	0.7	0.8							

Analysis of results of cleaning		365	404	464	522	624	760	970	365	404	464	522	624	760	970
		Reflectivity % per waveband (nm)							"Dust Indices"						
ΔR%	change due to CO2, whole mirror	2.5	2.6	2.7	2.9	2.9	3.1	3.6	-1.9	-2.3	-3.1	-3.1	-4.2	-4.5	-5.0
	average over wave bands							2.9							-3.5
	change since 9 January	0.8	0.8	0.8	0.9	0.9	1.0	1.0	-1.0	-1.0	-1.4	-1.1	-1.7	-1.8	-1.8
Averages 7 Dec 2016, omitting located minima		90.9	89.5	89.1	89.2	88.4	85.8	91.9	5.8	5.6	5.7	4.5	5.1	4.2	4.2
ΔR%	since 7 Dec 2016, **omitting minima**	0.1	0.1	0.1	0.1	0.2	0.1	0.2	-0.3	-0.6	-0.6	-0.5	-0.8	-0.7	-0.7

Comparison by quadrant of mirror - has any one of the 4 been cleaned more effectively than another? Omit minima from these averages:

ΔR%	left side average change	2.3	2.3	2.4	2.6	2.7	2.8	3.3	-1.6	-2.1	-2.8	-2.6	-3.5	-3.9	-4.3
	top quadrant avg change	2.3	2.4	2.4	2.7	2.7	2.8	3.3	-1.7	-2.1	-2.7	-2.6	-3.7	-4.0	-4.5
	right side average change	2.6	2.8	2.9	3.0	3.2	3.2	3.8	-2.2	-2.6	-3.5	-3.5	-4.7	-4.9	-5.5
	bottom quadrant avg chg	2.7	2.7	2.8	3.0	3.1	3.3	3.7	-1.8	-2.4	-3.2	-3.2	-4.6	-4.8	-5.4

Note: Minima that deviate by approx. 2σ from the mean are omitted from some comparisons, as they most likely represent unreduced stains.

Discussion:

There is a consistent ~1% improvement w.r.t values after CO2 in January, surprising but clearly significant compared to measurement errors.
There is even a marginal %R improvement with respect to averages from 7 Dec 2016 (14 weeks ago), with scattering significantly improved, by ~ 0.5%.
Cleaning results are 10-20% better in the right hand and bottom quadrant, compared with the other quadrants.
This is probably a bias caused by ease of reaching those areas. Note the bottom was cleaned a second time with N48 and once more with Aligal2.
The range of values has also been significantly reduced, meaning the reflectivity measurements are about as uniform as in December.
As observed previously, ΔR% and Scattering improvements are ~2x larger in red wave bands than in blue.

Conclusion: This CO2 cleaning was unusually effective, leading to the largest improvement since May 2015, in terms of percentage changes.
It was 5x more effective than the previous two cleaning (7 Dec and 9 Jan). It appears to have removed dust present since before the previous cleaning.
Note that the December cleaning had **less margin** for improvement. It's not clear why the January cleaning had been relatively ineffective.
It may have been due to using the end of the CO2 bottle, or the slightly higher humidity then (30%). It remains to be seen if the next CO2 can
make any gain on levels of reflectivity measured before December.