

Introduction

Under contract to NASA, NanoLab developed several coating processes to produce very high absorbance optical blacks for stray light suppression. The original Singularity Black required a 300°C bakeout and was replaced with the Low Temperature (LT) version to enable its use on more substrates. NanoLab offers two coatings to meet the needs of optical engineers:

- IM-1.6- designed for absorbance of light at glass to coating interfaces
- Singularity Black LT Aero (SB-LT)-for absorbance at air to coating interfaces.

Singularity Black Overview

Singularity Black paints are carbon nanotube filled, solvent-based paints that have world class performance in the visible, NIR and IR (typically below 1% reflectance in the visible), exceeding the optical properties of other commercially available products like Aeroglaze Z307 and Martin Black. Singularity Black's grazing angle performance is unmatched. Singularity Black paints are field repairable, should a coating become scratched or damaged.



Coating Services and Contact Information

In addition to selling the coatings, NanoLab provides coating services for baffles, telescope components, and other optical parts. Parts are handled in ISO class 5 clean spaces to prevent particulate contamination during the coating process. All work is done domestically, by US citizens in an ITAR compliant facility. Email sales@nano-lab.com for product quotes and coating services. Automated sprayers enable high throughput coating, and coating of complex internal geometries.

Singularity™ Black Training & Packaging

For those interested in painting components, we offer a Singularity School where students will learn safety protocol, and application techniques to make the deepest blacks possible. These courses can be held at NanoLab, or at your facility. We sell Singularity Black in four sizes: 20 ml vials, pints, quarts and gallons. These are shipped internationally via Fedex as dangerous goods.



Singularity Black Application

Air brush/ HVLP spraying is the recommended application technique. Dipping or manual brushing as application methods will not result in the same structure nor the same level of blackness.

Equipment

The equipment on the list below is in use at the NanoLab facility. It is strongly recommended to use similar equipment for paint application and clean part handling. Additionally, cleaning supplies (isopropyl alcohol, acetone, de-ionized water), swabs and other tools are required to clean and maintain the spray guns.

Ultrasonic bath	Solvents and detergents for part cleaning as needed
Spray booth	ventilation, 100 linear fpm minimum
Airbrush	Iwata Eclipse HPCS, or HP-TH2,
Air Supply	Clean, dry air supply, 1-2 CFM at 60-65PSI
PPE	Gloves, solvent vapor/particulate masks
Oven	140°C +/- 10C with 10-minute timer
Environment	ISO 5 clean bench for part handling before and after coating, curing and while packaging.



Material substrates suitable for Singularity Black Paints

Substrates and spray guns for SB-LT should be resistant to chemical attack from solvents such as methyl ethyl ketone and tetrahydrofuran. All surfaces should be free from loose particulate and organic residues that may reduce paint and primer adhesion. NASA specification PRC-5001 "Process Specification for Cleaning of Hardware" defines levels of cleanliness. Parts that are "VC-HS" (Visibly Clean-Highly Sensitive) per this specification have produced adherent, highly black coatings on the following materials:

Metals			
Aluminum alloys 2024, 6061	Chromate conversion coated aluminum (DTL Type 2, Class 1A)	Anodized aluminum (Type II, clear or PAA)	Mild & stainless steels
Nickel	Molybdenum	Copper	Titanium
Plastics			
Ultem 1010 (FDM)	Antero 840CN03 (carbon fiber filled PEKK) (FDM)	Antero 800NA (FDM)	Somos PerFORM (SLA)
Oxides			
Glass	Sapphire	Magnesium oxide	Aluminum oxide

Primer

Properly cleaned Al and conversion coated Al parts do not require a primer. For some metals (particularly copper), carbon fiber composites, and some plastics, we recommend a pretreatment with a primer to enhance the adhesive strength of the paint-substrate interface. Parts can be either sprayed (with the above airbrushes) or dipped in CarboLok, mixed at 5 wt.% in isopropanol.



After drying, this pretreatment leaves only a molecular layer thickness which does not measurably change the part dimensions. This silane-like treatment increases the bond strength of the coating-substrate interface beyond the cohesive strength of the coating. Consult with NanoLab staff for details on CarboLok.

Painting with Singularity Black

Paint Preparation

SB-LT is delivered in a ready to spray condition as a single component paint, No dilution or addition of second part is required. Paint should be agitated manually, mechanically or ultrasonically before use. Use lids to reduce evaporation of the paint in the sprayer-cup. The viscosity of fresh SB-LT can be measured using a Zahn #2 cup. As produced, the Zahn cup time should be 20 seconds +/-10 seconds. For planning of a spray job, prepare enough paint to utilize up to 1ml per cm² of surface area to be painted. Unused paint may be returned to the container.

Coating

The proper gun to substrate distance for an airbrush or spray gun is determined by observing the deposited film: at no time should the coating appear wet on the surface, which indicates distance is too short or paint flow is too high. At too far a distance, the paint arrives at the surface already dry and will not adhere. For many airbrushes and sprayguns, a distance of ~10 cm (4"), is appropriate, but this varies depending on gun settings, and distance should not be used as a requirement.

Additional coats may be applied after flashoff has been observed. The flash-off is visually accompanied by a slight darkening of the coating. This typically occurs within a few seconds.

Multiple light coats help to build the porous structure that enhances the light trapping properties of the coating.

Note that the reflectance of the coating is specified as <1% THR at 600nm. The thickness of the coating is not specified, as experienced operators can achieve the reflectance target with less paint than inexperienced operators. Contact based thickness measurements may crush the porous structure and are not recommended. For planning purposes, experienced operators achieve the specified reflectance with a coating of approximately 50 microns in thickness.

Environment (humidity and temperature)

While there are no specified ranges for humidity or temperature for proper application of Singularity Black, there are several factors to be aware of. As the solvent evaporates out of the deposited coating, the part will cool. If the ambient humidity is high enough, water may condense from the atmosphere and deposit on the part. The condensation of water on the parts should be avoided. If that occurs, provide additional time between coats to let the water evaporate.

The evaporation rate of the solvent in the paint is proportional to temperature. Lower temperatures will slow the flashoff process, while elevated temperatures will accelerate the flashoff process. Ranges of temperature and humidity for the painting facility should be determined for operator comfort.

Cure

After spray application, a heating step is required to crosslink the coating. Once crosslinked, it is a 'low touch' surface, tough enough for gentle handling. Parts coated in Singularity Black paint can be cured by inserting the parts in an oven set at 140°C +/-10C. After inserting the parts, wait for the oven temperature to return to at least 130C, before starting a timer, then cure the parts for minimum of 10 minutes to crosslink the binders and create a durable coating. There



is no maximum heating time. Large parts may require instrumentation to monitor the temperature.

Analytical & Quality Control

To confirm that the coating has achieved its potential for sub 1% reflectance in the visible, NanoLab coats a witness sample with each coating job. Unless otherwise specified, that witness sample is a 2" square sheet of 6061 aluminum, which receives the same pretreatment and number of coats as the parts. That sample is baked alongside the parts, and then analyzed for total hemispherical reflectance. A UV-Vis Spectrometer equipped with an integrating sphere is used to measure the reflectance of the witness sample across the visible range.

If dry film thickness must also be measured, a mild steel witness sample of similar dimensions is also coated. We use a magnetic thickness gauge such as the Elcometer 211, as the coating is conductive, making eddy current measurements are inaccurate.

Handling, Cleaning & Packaging of coated parts

Parts are to be handled with care after coating, and coated surfaces are considered no-touch surfaces. If necessary, compressed dry air can be blown over coated areas to remove FOD. Singularity Black is hydrophobic, so alternatively, clean water can be used to lift dust off a surface. CO₂ snow cleaning of coated surfaces has also been demonstrated. Coated surfaces should NOT be cleaned with isopropyl alcohol. If a solvent must be used nearby coated areas, hexane is recommended, as its low surface energy will allow it to dry without changing the surface structure.

Packaging solutions should be designed to minimize contact with any coated surfaces. We often design 3D printed packaging solutions to protect parts from damage during shipping. We typically utilize heat sealed cleanroom bags for inner packaging and a press to close bag for outer packaging. Packaging and handling at the NanoLab facility is conducted within an ISO Class 5 clean bench.

Safety, Storage and Shelf Life of Singularity Black products

The shelf life of SB-LT is six (6) months from date of production when stored in the original, unopened container at temperatures between 4-30°C.(39-86°F). Store indoors away from heat, sparks, and open flames. The pot life of SB-LT is determined exclusively by evaporation of solvent and the accompanying increase in viscosity. In some circumstances, an overly viscous paint can be thinned with tetrahydrofuran and returned to sprayability.

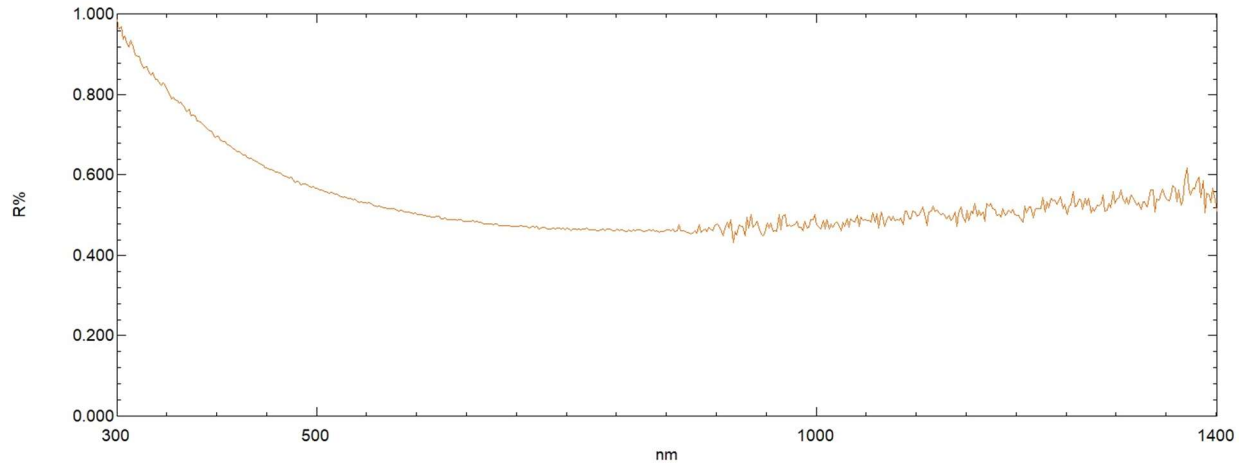
The viscosity of fresh SB-LT can be measured using a Zahn #2 cup. As produced, a time of 20 seconds +/-10seconds indicates a good paint. Overly evaporated paint becomes concentrated and is difficult to spray. A good indicator is a viscosity greater than 160 cP (Zahn #2 cup, >60 seconds). Review the SDS for safety information on Singularity Black products.

Singularity Black, Properties of coated articles

Singularity Black Optical & IR performance

Total Hemispherical Reflectance (THR)

Singularity Black samples were measured at NanoLab, using our research grade UV-Vis-NIR spectrometer equipped with an integrating sphere, and measured referenced to a Spectralon white sample. Parts sprayed with Singularity Black can achieve sub 1% THR at 600nm.



BSDF

Bidirectional Scatter Distribution Function measurements were taken in 2022 at The Scatterworks, using their Complete Angle Scatter Instrument (CASI) with the source at incidence angles of 10, 30, 55 & 70 degrees. The detector scan radius covers the range +/- 90 degrees to the surface normal. The test wavelength was 1.06 micron. Contact NanoLab for data files.

Outgas Testing

Outgassing tests on paint chip samples of SB-LT Aero were performed in April, 2023 by Aerospace & Advanced Composites GmbH, Austria, according ECSS-Q-70-02, The test is akin to ASTM E595 and was conducted at 125°C and 8×10^{-7} Torr. The coating passes acceptance limits for ECSS-Q-70-02, which require the mean values be: TML < 1.0 %, RML < 1% and CVCM < 0.10 %.

TVT2310

Material (See also material identification cards.)	TML		RML		WVR		CVCM		Acceptance limits achieved:
	Mean [%]	StdDev [%]	Mean [%]	StdDev [%]	Mean [%]	StdDev [%]	Mean [%]	StdDev [%]	
CN98A	0,39	0,01	0,18	0,03	0,21	0,03	0,06	0,00	YES
CN98B	0,48	0,03	0,20	0,04	0,28	0,07	0,02	0,01	YES
CN98C	0,35	0,04	0,06	0,02	0,28	0,04	0,04	0,03	YES
CN98D	0,37	0,04	0,08	0,03	0,29	0,05	0,00	0,01	YES

Acceptance limits (customer defined; not acc. to ECSS Q-70-02)

Actual value must be lower (<) than limit (not <=).	1,00	0,05	1,00	0,05			0,10	0,03
	1,00	0,05	1,00	0,05			0,10	0,03
	1,00	0,05	1,00	0,05			0,10	0,03
	1,00	0,05	1,00	0,05			0,10	0,03

Acceptance limits achieved:

CN98A	YES	YES	YES	YES			YES	YES	YES
CN98B	YES	YES	YES	YES			YES	YES	YES
CN98C	YES	YES	YES	YES			YES	YES	YES
CN98D	YES	YES	YES	YES			YES	YES	YES

Acceptance Limits (acc. to ECSS Q-70-02):

Mean value of the material must be: RML < 1.0 % and CVCM < 0.10 %. (For special requirements refer to standard.)

The standard deviation (StdDev) of the TML and RML must be lower than 0.1 times the mean value, with a minimum of 0.05 %.

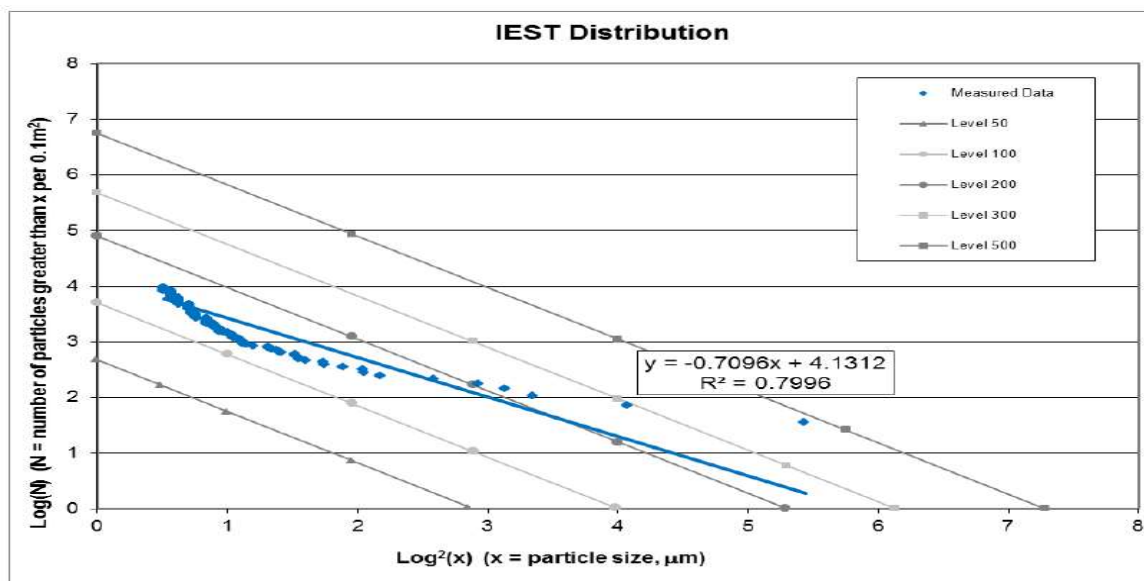
The standard deviation (StdDev) of the CVCM must be lower than 0.2 times the mean value, with a minimum of 0.03 %.

Cleanliness

The coatings are cleanable using gaseous nitrogen at low to medium pressure (5 to 50 psi). The process removes stray fibers and dust, but not the coating. Once cleaned, the coatings were measured with a Clemex particle counter. Many optical instruments have a requirement of Level 400 per Institute of Environmental Sciences and Technology (IEST) STD-CC1246E. Assemblies with slits or pinholes require Level 200. Painted hardware typically has a particle level higher than 500. The IEST equivalent for the Singularity sample was 127.

Total Particles	266	Total Area Counted (μm^2)	2.813E+09
Background Particles	0	Area of Particles (μm^2)	1.848E+04
		Percent Area Covered (PAC)	6.571E-04
Particles Analyzed (total - background)	266	Background PAC	0.000E+00
Particles Analyzed (total - background) per 0.1m^2	9457	PAC (total - background)	6.571E-04
		PAC rate	
		Equivalent IEST Level*	127

Particle Size μm	ALLOWABLE PARTICLES per 0.1m^2 BY IEST CONTAMINATION LEVEL					Number of Others per 0.1m^2	Number of Fibers per 0.1m^2	Total Particles per 0.1m^2
	100	200	300	400	500			
>25	78.4	1230	7450	28800	86300	284	36	320
>50	10.7	169	1020	3950	11800	142	36	178
>100	1	15.8	95	367	1090	36	36	71
>200		1	6	23.3	69.6	0	36	36
>300			1	3.9	11.6	0	0	0
>400				1	3	0	0	0
>500					1	0	0	0



Vibration

The Singularity coated panels successfully passed vibration testing. The GEVS vibration level is an input of 14.1 Grms that comes from the "General Environmental and Verification Specification for STS and ELV Payloads, Subsystems and Components", GEVS-SE, June 1996, Table 2.4-4. The BPL test is from a Ball Aerospace Structural Guideline and the vibe levels (also called Power Spectral Density or PSD) are high to account for design cases where responses cannot be

predicted. It includes a combination of vibe levels that account for acoustic vibration, random vibration, and quasi-static loading. This level is higher than most flight applications. No visible particles were removed during these tests. Some particles were generated by the vibration testing and characterized using the Clemex particle analyzer.

Vibe Level	GEVS				BPL			
Test Order	1	2	3	4	5	6	7	8
Sample	129-6	140-5	129-6	140-5	129-6	140-5	129-6	140-5
Axis	X	X	Z	Z	Z	Z	X	X
PC Test	15-0705	15-0708	15-0706	15-0707	15-0704	15-0703	15-0701	15-0702
micrometers	Particles per 0.1 m2							
>25	1201	426	543	659	504	465	1783	1473
>50	271	155	155	116	116	155	426	426
>100	0	116	0	78	0	116	310	194
>250	0	39	0	78	0	78	78	78
>500	0	0	0	78	0	78	78	39
Percent Area Covered (PAC)	2.86E-03	4.19E-03	1.19E-03	1.36E-02	1.19E-03	1.46E-02	2.53E-02	1.83E-02
TEST-CC-1246 Level	100	200	148	262	248	266	300	280
Comments	Dark	Dark	Mostly dark	Mostly black + 2 Blue	Mostly dark	Dark	None	Mostly black

Particle fallout levels during vibration testing were between IEST Levels 100 and 300, which are lower than what is observed for Martin Black and other black paints.

Thermal Stability Data

Samples were thermal cycled three times between -60°C and 85°C at a ramp rate of 10°C/minute, with 30-minute dwells at the extremes, in a nitrogen atmosphere. No damage or loss of particulate was noted. Also, thermal vacuum conditions, $<1e^{-6}$ torr at 100°C, did not affect the coating.

The safe upper operational limit for Singularity Black coating is 300°C in air, 400°C in vacuum, and safe lower operational limits for the coating are -200°C in air or vacuum.

The autogenous autoignition temperature for the coating is 600°C in air. Combustion products may include CO, CO₂.

Other

Conductivity	~150 ohm per square.
Emissivity	0.86
Absorptivity	0.99
UV Degradation	Expected high resistance ¹
Atomic Oxygen	Awaiting data from ISS MISSE study, expected high durability ²
Ionizing Radiation	Untested, expected improvement over unfilled polymers ³
Wetting	Hydrophobic.
Solvated odor	Ethereal
Dried odor	None
Density	1.2 g/cm3
Areal Weight	1.4 mg/cm2 at 50 micron

Estimates for Ultraviolet and Atomic Oxygen degradation are based on literature review for nanotube loaded polymeric composites.



1. "Effects of UV degradation on surface hydrophobicity, crack, and thickness of MWCNT-based nanocomposite coatings," R. Asmatulu, G.A. Mahmud, et al. Progress in Organic Coatings, Volume 72, Issue 3, November 2011, Pages 553-561
<https://doi.org/10.1016/j.porgcoat.2011.06.015>
2. "Reactive Molecular Simulation of the Damage Mitigation Efficacy of POSS-, Graphene-, and Carbon Nanotube-Loaded Polyimide Coatings Exposed to Atomic Oxygen Bombardment," F.Rahmani, S.Nouranian, et al. ACS Appl. Mater. Interfaces 2017, 9, 14, 12802–12811, <https://doi.org/10.1021/acsami.7b02032>
3. "Ionizing Radiation Effects on Interfaces in Carbon Nanotube-Polymer Composites", J.. Harmon, P.. Muisener, M. Meyyappan, A. Cassell, MRS Online Proceedings Library (OPL) , Volume 697: Symposium P – Surface Engineering 2001--Fundamentals and Applications , P9.7 <https://doi.org/10.1557/PROC-697-P9.71>