Analysis of Age-Related Color Change of GEO Satellites via Spectroscopy

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CONFERENCE PAPER

The SSA community has performed research in the past to suggest that resident space objects (RSOs) may have age related color changes. That is, they have increased flux in the bluer wavelengths or decreased flux in the redder wavelengths (blueing), or increased flux in the redder wavelengths or decreased flux in the bluer wavelengths (reddening) with age. The goal of our research is to investigate the color change of Geosynchronous Earth Orbit (GEO) satellites with age. Using the Falcon Telescope Network, we plan to observe groups of GEO satellites, under similar illumination conditions (longitudinal phase angles), that are considered identical (as closely as possible) but of differing ages (time on orbit) to look for a relationship of color change with age.

By identical GEO satellites, we mean a common bus type, solar panels, contractor, operator, and equipment. The planned targets of this research leverage previous work in the area of age-related color change. The planned targets have as many attributes as a controlled variable as possible and only the age as a dependent variable, avoiding the risk of mixed RSO types and a mixture of technology. Determining a color change with age will help to characterize GEO satellites. GEO satellites change their brightness throughout the night (timescales of minutes or hours) as the illumination conditions change relative to a ground-based observer. A GEO satellite's signature may also change seasonally (timescales of weeks or months) as the angle of the Sun, satellite, and observer change. This is most noticeable during glint season. A color change with age would be another change for GEO satellites, on timescales of years, that needs to be understood and accounted for.

Observations of multiple groups with varying bus type spanning up to 5 years on-orbit time difference revealed no obvious reddening or any age-related color change.

1. INTRODUCTION

There is the general belief within the SSA community that RSOs redden due to space environment effects, appearing to be material dependent but independent of orbit and age [1]. Recent research of objects on orbit has not proven this to be the case. Pearce et al. spectroscopically observed five Russian SL-12 rocket bodies showed the color change of bluing with age; more specifically their flux decreased in the longer (redder) wavelengths with years on orbit [2]. Other research has shown mixed or inconclusive results [3,4]. Part of this is due to the RSO sample being a mixture of RSO types (rocket bodies, debris, and GEO satellites) [3], and a mixture of solar panel technology on a common GEO bus type [4]. While the first group found bluing with age for rocket bodies of one group, the second group showed no relationship with age. Yet another research group found no color change with age for three bus types, but did observe a fourth bus type which showed an apparent bluing with age [5].

In an attempt to clarify age-related color changes, we created a list of identical GEO satellite groups that were launched at different times and observed some of these satellite groups outside of glint season to obtain spectroscopic measurements and hyperspectral signatures at similar small longitudinal solar phase angle (< 5º) illumination conditions. Observations outside of glint season are expected to be much less dynamic and provide a measure of color differences between group members, as suggested by [5] in their photometric color study. By comparing the measured color differences as a function of on-orbit age difference, any age-related color changes will become manifest.

2. TARGET LIST

The target list was created based on the idea of finding groups of identical GEO satellites but of varying ages in orbit such that they could be observed with the Falcon Telescope Network (FTN) and their spectra could be analyzed to investigate color change with age. Gunter's Space Page[1] contains groupings of identical satellites. Identical in terms of operator, contractor, equipment, bus type (configuration), and presumed solar panels. The final target list is shown in Table 1 and is populated with 16 groups of identical GEO satellites. From Gunter's Space Page, the fields 'Satellite Name', 'Bus Type', and 'Launch Date' were populated. Then the age was calculated from the 'Launch Date'. N2YO.com[2] was used to populate the 'Inclination' and 'Longitude Slot'. Once the 'Longitude Slot' was populated, the FTN sites that could be used for observing each GEO satellite was determined using an elevation of 20 degree or larger.

Table 1. GEO target list for groups of identical satellites

Group Number	Satellite Name	Satellite Number	Bus Type	Launch Date (YYYY-MM-DD)	Age (Years, Decimal)	Age Relative to Earliest Launch (Years)	Inclination (degrees)	Longitude Slot (degrees)
Group 1	AMC 11	28252	A2100A	2004-05-19	18.71	0.00	0	-111.1
	AMC 18	29644		2006-12-08	16.15	2.56	0	-83
Group 2	SES 1	36516	Star-2.4 Bus	2010-04-24	12.78	0.00	0	-100.99
	SES 3	37748		2011-07-15	11.55	1.22	0	-103
Group 3	XM 3	28626	BSS-702	2005-03-01	17.93	0.00	0	-85.08
	XM 4	29520		2006-10-30	16.26	1.67	0	-39.01
Group 4	DTV 10	31862	BSS-702	2007-07-07	15.58	0.00	0	-102.81
	DTV 11	32729		2008-03-19	14.88	0.70	0	-99.2
	DTV 12	36131		2009-12-29	13.10	2.48	0	-102.71
Group 5	GOES 16	41866	A2100A	2016-11-19	6.21	0.00	0	-75.19
	GOES 17	43226		2018-03-01	4.93	1.28	0	-104.73
	GOES 18	51850		2022-03-01	0.93	5.28	0	-137.01
Group 6	Intelsat 901	26824	SSL-1300HL	2001-06-09	21.65	0.00	0	-27.5
	Intelsat 902	26900		2001-08-30	21.43	0.22	3.2	-50.09
	Intelsat 904	27380		2002-02-23	20.94	0.71	4.1	-29.51
	Intelsat 905	27438		2002-06-05	20.66	0.99	3.9	-24.51
	Intelsat 906	27513		2002-09-06	20.41	1.24	2.9	64.2
Group 7	Skynet 5A	30794	Eurostar-3000S	2007-03-11	15.90	0.00	2.4	95.28
	Skynet 5B	32294		2007-11-14	15.22	0.68	2.4	25.12
	Skynet 5C	33055		2008-06-12	14.64	1.25	0.9	-17.8
	Skynet 5D	39034		2012-12-19	10.12	5.78	0.1	52.79
Group 8	WGS 1 (USA 195)	32258	BSS-702	2007-10-11	15.31	0.00	0	6
	WGS 2 (USA 204)	34713		2009-04-04	13.83	1.48	0	57.46
	WGS 3 (USA 211)	36108		2009-12-06	13.16	2.15	0.4	-42.79
Group 9	WGS 8 (USA 272)	41879	BSS-702	2016-12-07	6.16	0.00	0	149.81
	WGS 9 (USA 275)	42075		2017-03-19	5.88	0.28	0	-12.01
	WGS 10 (USA 291)	44071		2019-03-16	3.88	2.27	0	60.27
Group 10	TDRS 11 (TDRS K)	39070	BSS-601HP	2013-01-31	10.01	0.00	2.7	-174.35
	TDRS 12 (TDRS L)	39504		2014-01-24	9.02	0.98	3.6	-41.01
	TDRS 13 (TDRS M)	42915		2017-08-18	5.46	4.55	4	-11.38
Group 11	Eute Hot Bird 13B (HB 8)	29270	Eurostar-3000	2006-08-04	16.50	0.00	0.1	13.05
	Eute Hot Bird 13C (HB 9)	33459		2008-12-20	14.12	2.38	0.1	13.03
	Eute 3C (HB 10)	33750		2009-02-12	13.97	2.53	0.1	33.12
Group 12	Astra 2E (Eutelsat 28E)	39285	Eurostar-3000	2013-09-29	9.35	1.00	0.1	28.53
	Astra 2F (Eutelsat 28F)	38778		2012-09-28	10.35	0.00	0.1	28.2
	Astra 2G (Eutelsat 28G)	40364		2014-12-27	8.10	2.25	0.1	28.25
Group 13	Inmarsat-4 F1 (Inmarsat I-4 F1)	28628	Eurostar-3000GM	2005-03-11	17.90	0.00	3.9	143.45
	Inmarsat-4 F2 (Inmarsat I-4 F2)	28899		2005-11-08	17.24	0.66	3.8	63.98
	Inmarsat-4 F3 (Inmarsat I-4 F3)	33278		2008-08-18	14.46	3.44	3.4	-97.99
Group 14	AMC 1	24315	A2100A	1996-09-08	26.40	0.00	6.4	-130.75
	AMC 3	24936		1997-09-04	25.41	0.99	5.4	-72.07
Group 15	GOES 13	29155	BSS-601	2006-05-24	16.70	0.00	1.5	61.32
	GOES 14	35491		2009-06-27	13.60	3.09	0.3	-108.47
	GOES 15	36411		2010-03-04	12.92	3.78	0.3	-149.51
Group 16	Spaceway 2	28903	BSS-702	2005-11-16	17.21	0.00	2.7	-138.87
	Spaceway 3	32018		2007-08-14	15.47	1.74	1.1	-94.96

[1] Gunter's Space Page (https://space.skyrocket.de/)

[2] N2YO.com (https://www.n2yo.com/)

The objective of the observations is to observe the GEO satellites on the same night for targets that are to be compared, with a common longitudinal phase angle. These observations take place outside of glint season so that the brightness and color change is less dynamic.

Many GEO satellites did not make it to the final target list. GEO satellites with a perigee indicating they were not in GEO but rather GEO graveyard were discarded. Whereas GEO satellites are three-axis stabilized and their illumination conditions are cyclical and predictable, i.e., exposure to solar radiation, graveyard GEO satellites will not be stabilized and will not have the same predictability. In addition, graveyard GEO satellites often have an inclination, sometimes large, which makes their observation more difficult. The inclination in general was reviewed and GEO satellites whose inclination was quite large were marked as unfavorable due to their difficulty in observing.

Multiple criteria were examined to prioritize the identical satellite groupings as "favorable" to include in the target list: 1. GEO satellites in the same identical group that were in close proximity, such as the same FOV, 2. Identical groupings that could be observed with one FTN site, 3. Identical groupings that could be observed with at most two FTN sites and had at least three targets, and 4. Identical groupings with a large range in age with the group.

There is the question of whether it is worth observing GEO satellites in an identical group if their age spread is not large. These closely spaced in age GEO satellites offer a control in that we expect little color change between them. Whereas those with a larger spread in age may be expected to show a color change. If the closely spaced in age GEO satellites showed a color change, then this indicates that there is another variable at play since this violates anticipated behavior for the assumptions made.

Initially, two FTN sites were available to conduct these observations: Technische Universität Braunschweig, Germany (TUBS) and Colorado Mesa University, Colorado (CMU). Table 1 lists all 16 groups generating from the original criteria and highlights those groups observable by these two sites. Groups observable from TUBS only are highlighted in yellow while groups observable from CMU only are highlighted in green. For some of these groups, the subset of objects observable from the single site are also highlighted. Due to weather and equipment issues, only the six groups observable from CMU were observed. These observations were conducted on UT 2023 Jun 23, 25, 26, 29, and Jul 01 and are detailed in the next section.

3. OBSERVATIONS AND RESULTS

Slitless spectroscopy has been a mainstay of FTN observations and research for many years [6-10]. Each night of observations include images of pixel-to-wavelength calibration stars, solar analog stars, and an extinction calibration star and these were used with the existing spectroscopy pipeline. Photometric conditions on UT 2023 Jun 26 allowed for establishing a wavelength dependent extinction correction and this was applied to all nights. The pixel-to-wavelength solution obtained on UT 2023 Jun 23 used on all data was 1.5329 nm/pixel with an offset of 13.7773 nm, which is very similar to previous measurements for the CMU site. All target satellites were observed for about 6-12 minutes spanning solar phase angles between -4 and 0 degrees to ensure similar lighting conditions for comparison.

The extracted spectra for each satellite ranges from 380 nm to 880 nm and interpolated to 1 nm increments for direct comparison to one another. Fig. 1 displays the spectra for SES1 from UT 2023 Jun 23. The left-hand plot is all extinction corrected spectral flux in counts per pixel per second for the given night while the middle plot is the same spectra in normalized flux while the right-hand plot is the wavelength-by-wavelength median value of the normalized flux. It is this final combined spectrum that will be used in the comparison.

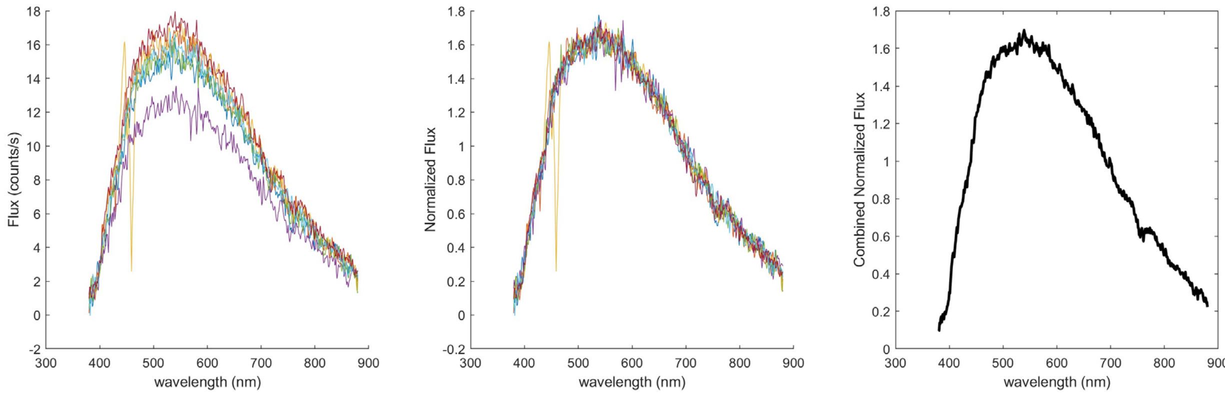

Fig. 1. Spectra of SES1 on UT 2023 Jun 23 – raw counts/s (left), normalized (center), median combined (right)

To compare one spectrum to another, a reddening value was calculated by summing up the difference between the median-combined normalized spectra with a linear weight based on wavelength. The weighting function is -1 at 380 nm to 0 at 630 nm to +1 at 880 nm. As such, a positive reddening value is obtained both if the flux difference between the newer object and older object is negative for bluer wavelengths (<630 nm) and positive for redder wavelengths (>630 nm). The same reddening value can be used to compare all spectra to a common baseline. Fig. 2 displays the calculated reddening value for each object when compared against a solar analog spectrum obtained from the observed solar analog calibration stars. The various groups from Table 1 are identified with the values color coded by night of observation (left) or the mean value of all nights the object was observed (right). It is clear that different satellite groups exhibit different colors. For example, whereas GEOs in groups 1 and 2 have more solar-like spectra, the other groups exhibit redder spectra. For those satellites with measured values over multiple nights, the mean standard deviation between measurements is about 0.0032 giving an indication of the uncertainty in each measurement.

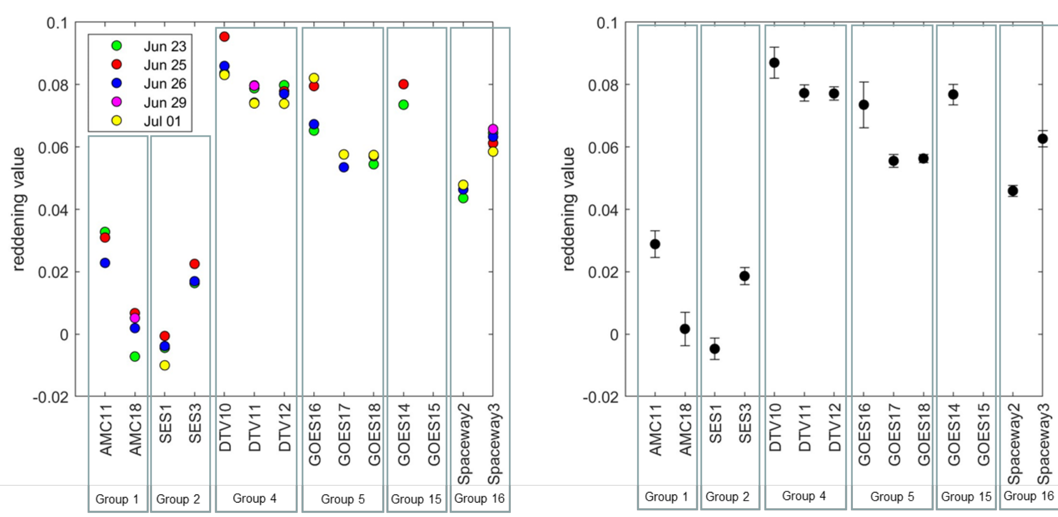

Fig. 2. Reddening value as function of GEO object identified delineated by night (left) and mean value (right). Note that no good observations of GOES-15 (group 15) were obtained on any of the nights.

For a given day, the spectra between satellites in a particular group were then compared. Fig. 3 displays such a comparison for Group 2 (SES1 & SES3). The spectrum for each is the median combined normalized flux. In this particular case, the two spectra are very similar yielding a reddening value of -0.0201. In the left-hand plot of Fig.

3, the spectrum of the older on-orbit GEO SES1 (red) is slightly bluer than the spectrum of the newer on-orbit GEO SES3 (blue). In the right-hand plot where the younger on-orbit spectrum (SES3) is divided by the older on-orbit spectrum (SES1), the observed bluing with age is caused by both a suppressed blue (less than one) and elevated red (greater than one) for the younger spectrum.

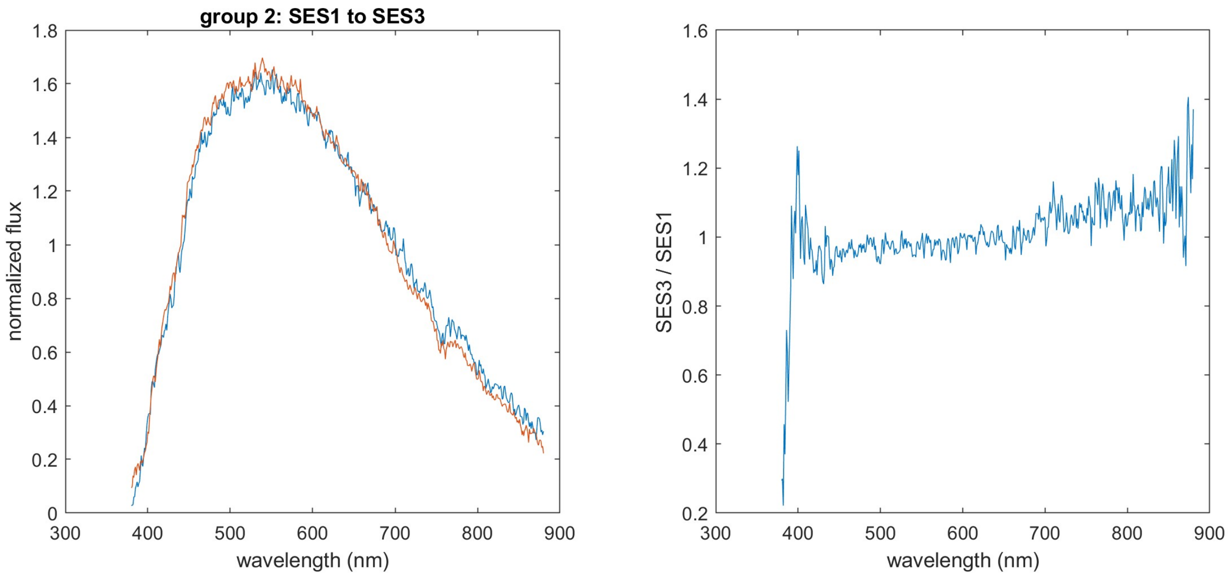

Fig. 3. Normalized spectra for SES1 (red) and SES3 (blue) (left) and SES3 spectrum divided by SES1 spectrum (right) for UT 2023 Jun 23. SES3's spectrum is both suppressed in blue and elevated in red as compared to SES1's spectrum.

Fig. 4 plots the reddening value as a function of on-orbit age difference for all groups and dates observed. As with Fig. 2, the left-hand plot shows each night's calculated value while the right-hand plot is the mean and standard deviation of all nights observed where different groups are designated by different symbols. There are noticeable and consistent differences in color between GEOs in the same group. For example, Group 2 at 1.22 years shows an apparent bluing for all three nights as shown previously in Fig. 3 (note that the UT 2023 Jun 23 reddening value is identical to the UT 2023 Jun 26 value and so the green dot appears absent but is in fact directly behind the blue dot). Group 1 at 2.56 years shows the highest value of apparent reddening for all three nights (note that the UT 2023 Jun 23 reddening value is significantly higher than the other two nights possibly due to poor spectra for AMC18 on that particular night). For the two groups with three members (Group 4 and Group 5) and thus three separate pairings in the plot, there is no apparent bluing or reddening trend with age, nor is there an apparent general trend with age.

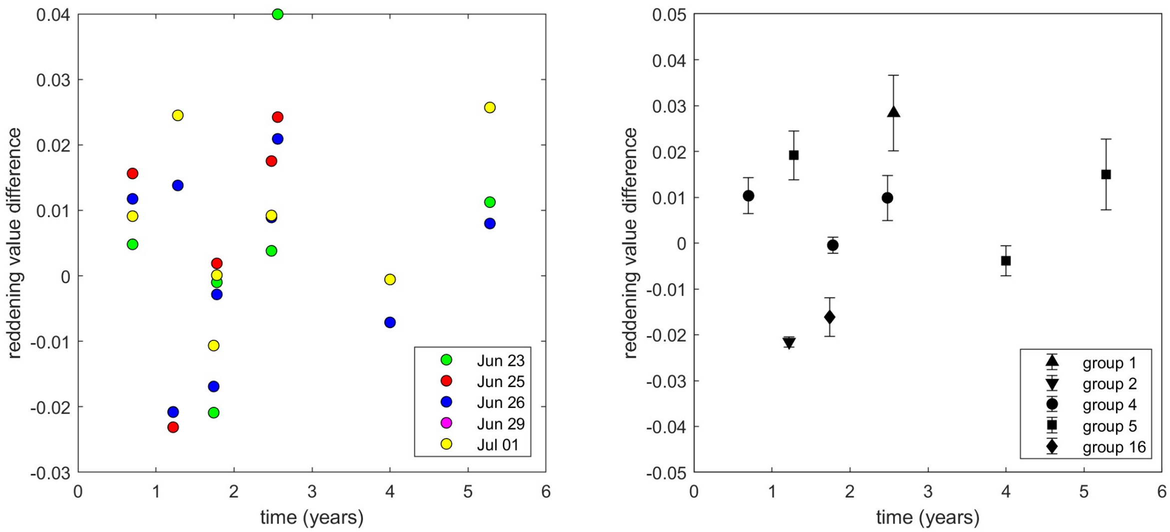

Fig. 4. Reddening value as function of on-orbit age difference delineated by night (left) and mean value (right).

When examining the individual objects, of particular note are the spectra of Group 16 (Spaceway-2 and Spaceway-3). Whereas all other GEOs observed show a nondescript spectrum consistent with being well outside of the so-called "glint season" of the solar panels, both Spaceway GEOs showed significant glinting that in some cases varied considerably over the 12-minute observation span. Fig. 5 displays the normalized flux spectra for both GEOs on UT 2023 Jun 26. For Spaceway-2, the spectrum starts with significant wavelength-dependent glinting off the bus that reduces to the diffuse background over the observation span. Spaceway-3 shows similar although smaller glinting with similar spacing between wavelength peaks, but with the peaks at different wavelengths. The source of the glinting and spectral features is unknown.

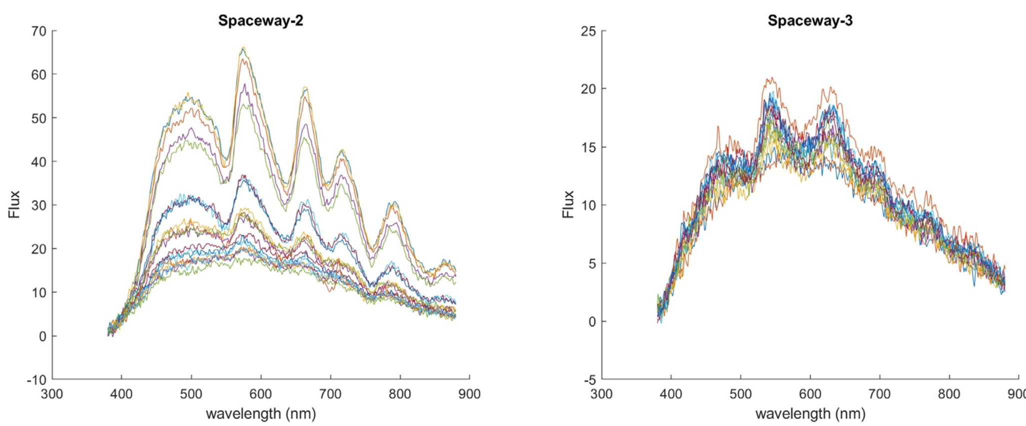

Fig. 5. Spectra (Flux vs. wavelength) of Spaceway-2 and Spaceway-3 on UT 2023 Jun 26.

4. SUMMARY AND CONCLUSIONS

The SSA community has looked for age related color changes in the past finding both bluing (increased flux in the bluer wavelengths or decreased flux in the redder wavelengths) and reddening (increased flux in the redder wavelengths or decreased flux in the bluer wavelengths) attributed to on-orbit age differences. In this study, after examining five identical groups of satellites with the Falcon Telescope Network over a 5-year range of on-orbit age difference, there was no obvious reddening or any age-related color change. However, definite color differences were noted between GEOs in each group, but these differences were not correlated with on-orbit age differences. It is likely these differences are simply inherent color differences between GEOs of the same bus type. Future studies should focus on comparing identically observed (same lighting conditions) and calibrated color estimations of the same GEO over time to assess age-related color changes directly.

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6. REFERENCES

1. Abercromby, K.J., M. Guyote, J. Okada, and E. Barker, “Applying Space Weathering Models to Common Spacecraft materials to Predict Spectral Signatures,” *The 2005 AMOS Technical Conference Proceedings*, (2005).
2. Pearce, E.C., B. Weiner, and H. Krantz, “Examining the effects of on-orbit aging of SL-12 rocket bodies using visible band spectra with the MMT telescope,” *J. Space Safety Engineering* 7 (2020) 376–380.
3. Cardona, T., et al., “BVRI photometric observations and light-curve analysis of GEO objects,” *Adv. Space Res*. 58 (2016) 514–527.
4. Frith, J., P. Anz-Meador, H. Coowardin, B. Buckalew, and S. Lederer, “Near-infrared color vs launch date: an analysis of 20 years of space weathering effects on the Boeing 376 spacecraft,” *The 2015 AMOS Technical Conference Proceedings*, (2015).
5. H.R. Schmitt, “Multi wavelength optical broad band photometric properties of a representative sample of geostationary satellites,” *Adv. Space Res.*, 65:1, pp. 326-336 (2020).
6. A. N. Dunsmore, J. Key, R. M. Tucker, E. Weld, F. Chun, and R. Tippets, *J. Spacecraft and Rockets*, 54, 349 (2016).
7. R. D. Tippets, S. Wakefield, S. Young, I. Ferguson, C. Earp-Pitkins, and F. K. Chun, *Opt. Eng*., 54 (2015).
8. Albrecht, E.M., A. M. Jensen, E.G. Jensen, K.A. Wilson, M.K. Plummer, J.A. Key, D.S. O'Keefe, F.K. Chun, D.M. Strong, C.P. Schuetz-Christy, “Near-Simultaneous Observations of a Geosynchronous Satellite Using Two Telescopes and Multiple Optical Filters,” *J. Astronaut Sci* (2022). https://doi.org/10.1007/s40295-021-00292-x
9. Reed, T.A., M.D. Parrish, J. Key, C.J. Wetterer, P. Castro, D.M. Strong, C. Schuetz-Christy, and F. Chun, “Optimization and Automation of the Spectroscopy Pipeline of the Falcon Telescope Network,” *The 2022 AMOS Technical Conference Proceedings*, The Maui Economic Development Board, Inc., Kihei, Maui, HI, (2022).
10. M.D. Parrish, J.A. Key, F.K. Chun, D.M. Strong, C.J. Wetterer, and P. Castro. Spectral analysis of unresolved satellite imagery. *Proceedings of SPIE: Algorithms, Technologies, and Applications for Multispectral and Hyperspectral Imaging*, 12094, 2022.