Preliminary Characterization of IDCSP Spacecrafts through a Multi-Analytical Approach

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ABSTRACT

Defining the risks present to both crewed and robotic spacecrafts is part of NASA's mission, and is critical to keep these resources out of harm's way. Characterizing orbital debris is an essential part of this mission. We present a proof-of-concept study that employs multiple techniques to demonstrate the efficacy of each approach.

The targets of this study are IDCSPs (Initial Defense Communications Satellite Program). 35 of these satellites were launched by the US in the mid-1960s and were the first US military communications satellites in the GEO regime. They were emplaced in slightly sub-synchronous orbits. These targets were chosen for this proof-of-concept study for the simplicity of their observable exterior surfaces. The satellites are 26-sided polygons (86cm in diameter), initially spin-stabilized, and covered on all sides in solar panels.

Data presented here include: (a) visible broadband photometry (Johnson/Kron-Cousins BVRI) taken with the 0.9m SMARTs telescope (Small and Medium Aperture Telescopes) at the Cerro Tololo Inter-American Observatory (CTIO) in Chile in April, 2012, (b) laboratory broadband photometry (Johnson/ Bessell BVRI) of solar cells, obtained using the Optical Measurements Center (OMC) at NASA/JSC [1], (c) visible-band spectra taken using the Magellan 6.5m Baade Telescope at Las Campanas Observatory in Chile in May, 2012 [2], and (d) visible-band laboratory spectra of solar cells using an ASD Field Spectrometer.

Color-color plots using broadband photometry (e.g. B-R vs. B-V) demonstrate that different material types fall into distinct areas on the plots [1]. Spectra of the same material types as those plotted in the color-color plots each display their own signature as well. Here, we compare lab data with telescopic data, and photometric results with spectroscopic results. The spectral response of solar cells in the visible wavelength regime varies from relatively flat to somewhat older solar cells whose reflectivity can be gently or sharply peaked in the blue. With a target like IDCSPs, the material type is known a priori, aiding in understanding how material type affects one's observations.

1. BACKGROUND

The Initial Defense Communications Satellite Program (IDCSP) was established by the United States in the mid-1960s. Between June of 1966 and June of 1968, the US launched 35 satellites (hereafter referred to as IDCSPs). These were the first US military communications satellites in the GEO regime. They were emplaced in slightly sub-synchronous orbits with orbital periods of 22.2 ±0.2h [3]. These targets were chosen for this proof-of-concept study for the simplicity of their observable exterior surfaces. The satellites are 26-sided polygons (86cm in diameter), initially spin-stabilized, and covered on all sides in solar panels. Their rotational period (spin) is unknown [3].

Fig. 1: The Air Force Space and Missile Museum at Cape Canaveral, Florida houses a model of an IDCSP [4].

2. PHOTOMETRY

2.1 Telescopic Setup and Data Reduction

Telescope: CTIO 0.9m SMARTS telescope, Cerro Tololo Inter-American Observatory (CTIO), Chile
Instrument: Tek 2048 x 2048 CCD
Feld of View: 13.69′ x 13.69′ field of view
Pixel size: 0.8″/pixel
Exposure times: B filter: 20 sec, VRI filters: 10 sec
Exposure sets: 10 images per filter per set, 1-3 sets taken per IDCSP
Filters: Johnson/Kron-Cousins broadband filters, Blue (B), Visible (V), Red (R), and Infrared (I)

Telescopic data were taken with the 0.9m SMARTs (Small and Medium Aperture Telescopes consortium) telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. IRAF (Image Reduction and Analysis Facility) software was used to extract photometric measurements for the IDCSPs [5, 6]. All data included in the analysis were taken under photometric conditions. Dome flat exposures were used to generate the master flat field for each filter. Data were bias subtracted and flat fielded in the standard manner. The IRAF PHOT task in the DAOPHOT package was used to extract photometry of objects. PHOT calculates the photometry within a circular aperture, and subtracts the sky median average within an annulus around the circular aperture. To improve the signal-to-noise ratio, the smallest possible aperture was chosen that included the full signal from the target object. Aperture sizes chosen for a given night, therefore, varied depending upon the seeing conditions.

GEO objects are moving at a significantly different rate than background stars, yielding star trails that may affect the photometry of the objects. Thus, data were visually inspected for contamination due to star trails. All observations with background star contaminations were eliminated from further analysis. Landolt standard star observations, covering a full range of colors and airmasses, were taken during the observing run and used to absolutely calibrate the observations [7].

Data were collected over four nights, April 19-22, 2012. Resultant color photometry of the 18 observed IDCSPs are given in Table 2. All colors given are weighted averages using 10 or 20 sets of BVRI images, weighted by the photometric errors (e.g. uncertainties due to sky and digital imaging using a Poisson model) of each photometric measurement. In contrast to the photometric errors, the standard deviations, σ(BV), σ(BR), and σ(RI) given in the table, are estimates of the variability of the color data over the set of 10 or 20 values of each color for a given object (i.e. these standard deviation values do not representing the photometric errors calculated by PHOT). The standard deviation values (i.e. ‘variability’) are plotted as error bars in Fig. 2.

Table 1: Telescopic photometry of IDCSPs

IDCSP #	SSN	V	B-V wt	s (BV)	R-I	s (R-I)	B-Rwt	s (BR)
1	**02215**	16.556	**0.813**	0.075	**0.738**	0.001	**1.315**	0.095
2	**02216**	17.158	**0.745**	0.122	**0.746**	0.001	**1.216**	0.148
3	**02217**	16.988	**0.712**	0.109	**0.738**	0.001	**1.223**	0.097
4		NA						
5		NA						
6	**02220**	17.473	**0.670**	0.195	**0.736**	0.001	**1.248**	0.181
7	**02221**	16.374	**0.606**	0.085	**0.744**	0.000	**1.096**	0.127
8	**02645**	17.620	**0.689**	0.134	**0.743**	0.001	**1.153**	0.149
9	**02649**	17.566	**0.737**	0.057	**0.738**	0.001	**1.306**	0.074
10	**02650**	17.205	**0.765**	0.070	**0.746**	0.000	**1.299**	0.064
11	**02651**	17.410	**0.755**	0.168	**0.743**	0.001	**1.310**	0.164
12	**02652**	14.534	**0.032**	0.045	**0.741**	0.000	**0.364**	0.031
13	**02653**	13.689	**-0.322**	0.057	**0.738**	0.000	**0.006**	0.085
14		NA						
15	**02655**	17.617	**0.668**	0.119	**0.747**	0.001	**1.223**	0.119
16	**02862**	17.645	**0.606**	0.125	**0.747**	0.001	**1.103**	0.083
17	**02863**	17.374	**0.798**	0.284	**0.739**	0.001	**1.482**	0.253
18	**02864**	16.384	**0.804**	0.055	**0.743**	0.000	**1.342**	0.061
19		NA						
20		NA						
21	**03285**	17.322	**0.680**	0.134	**0.737**	0.001	**1.226**	0.123
22	**03286**	NA	**0.959**	0.364	**0.736**	0.003	**1.629**	0.367
23	**03287**	17.347	**0.803**	0.067	**0.735**	0.000	**1.305**	0.081

2.2 Laboratory Setup

Laboratory: Optical Measurements Center (OMC), NASA's Orbital Debris Program Office
Setup: Analogous to a telescope set-up with a light source, target, and detector
Light source: 75-watt, Xenon arc lamp (simulates solar illumination from 2000 to 25000Å)
Instrument: Santa Barbara Instrument Group (SBIG) CCD camera, 1024 x 1536 pixels
Filters: Johnson/ Bessell filters: Blue (B), Visible (V), Red (R), and Infrared (I)

Laboratory measurements are acquired in a manner similar to telescopic measurements: an object is observed by a CCD camera with a light source illuminating the target. The laboratory uses a Xenon-arc lamp 'solar-simulator' light source instead of the Sun. The Xenon lamp is designed to approximate a 5800K blackbody, again, like the Sun. However, because the laboratory setup (Xe-source, optics, CCD) does not yield an exact spectral match to a telescopic setup, a correction factor must be applied. To simplify this process, the laboratory measurements are normalized such that a white reference (Spectralon panel) returns color values of 0 for all filter sets (e.g. B-V=0, B-R=0, R-I=0). To compare with targets in space, a solar correction must then be applied to all lab measurements (a.k.a. solar colors listed in Table 2 are added to each laboratory color measurement).

Johnson/ Bessell broadband BVRI filters and an SBIG camera were used to collect the laboratory data. Photometry was collected of spacecraft materials, including two newer black solar panels (Spectrolabs UTL and ITJ), two solar cells that are visually bluish to (Solar Cell 1 & 2), and a solar cell not used for spacecrafts (Non-S/C cell). All samples are more modern (1990s and later) solar cells, in contrast with the IDCSP solar cells.. We also include a non-spacecraft solar cell to demonstrate the difference in colors of other types of solar cells. See Cowardin [1, 8] for further details on laboratory setup and data collection.

Table 2: Laboratory samples with respective photometric color indices before (lab) and after (solar corr) solar correction.

Material	Source	B-V lab	B-V sol corr	B-R lab	B-R sol corr
Sun			***0.625***		***0.981***
UTL Solar panel	**filter photometry**	0.192	***0.817***	0.092	***1.070***
UTL Solar Cell	**spectrum**	-0.005	***0.620***	0.200	***1.178***
IITJ Solar cell	**spectrum**	0.073	***0.698***	0.476	***1.454***
Solar cell 1	**spectrum**	-0.134	***0.491***	0.023	***1.004***
Solar cell JPL	**spectrum**	-0.716	***-0.091***	-0.851	***0.127***
Non-S/C cell	**filter photometry**	0.153	***0.778***	-0.804	***0.177***

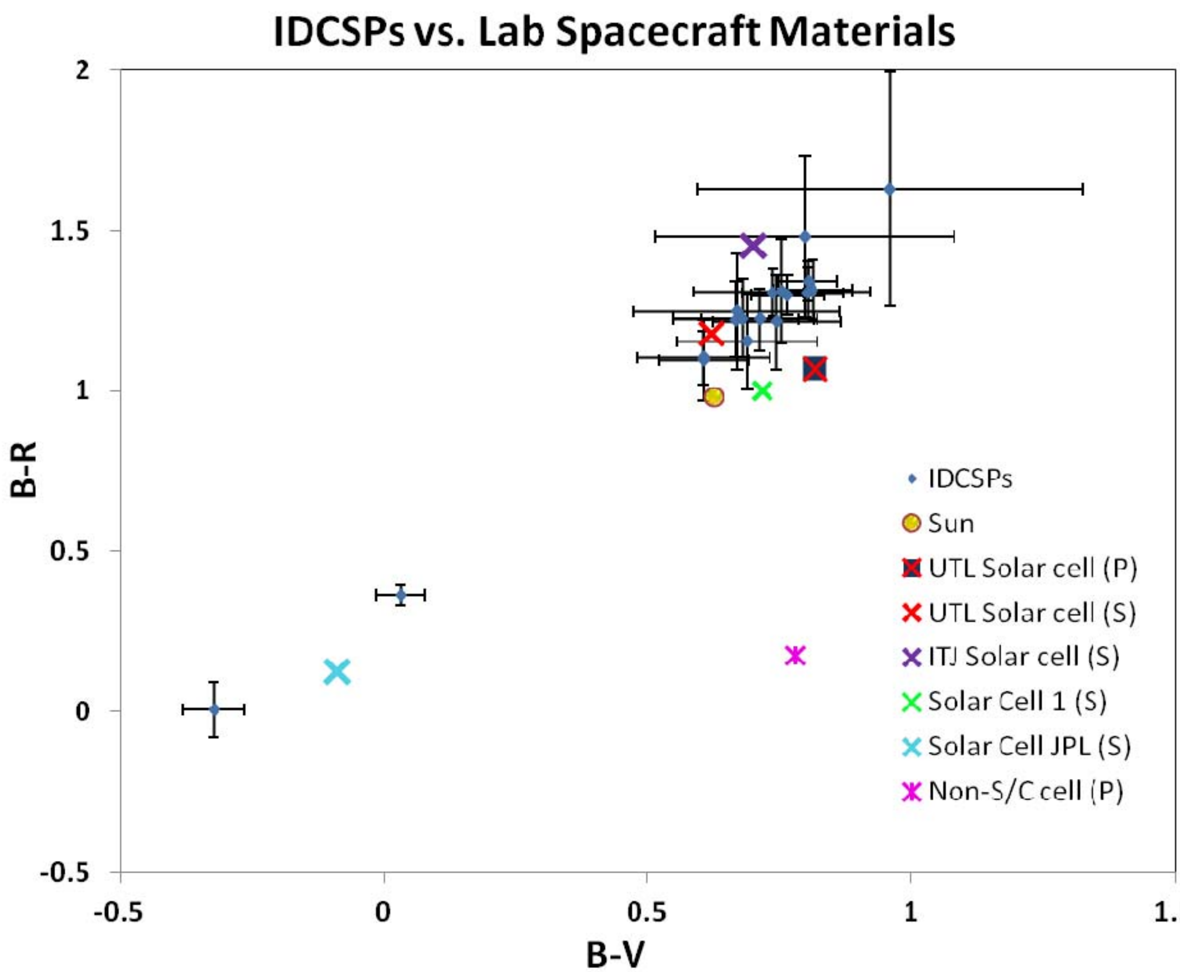

Fig. 2: Photometric B-V vs. B-V color indices for telescopic data of IDCSPs and laboratory measurements of various spacecraft materials. In all cases, the spacecraft material's solar corrected colors listed in Table 1 are plotted here. Values listed under "Sun" were used to correct laboratory values. One UTL solar cell, the ITJ solar cell and Solar Cell 1 values were derived from laboratory spectra. One UTL solar cell and non-spacecraft (S/C) cell were taken with filter photometry.

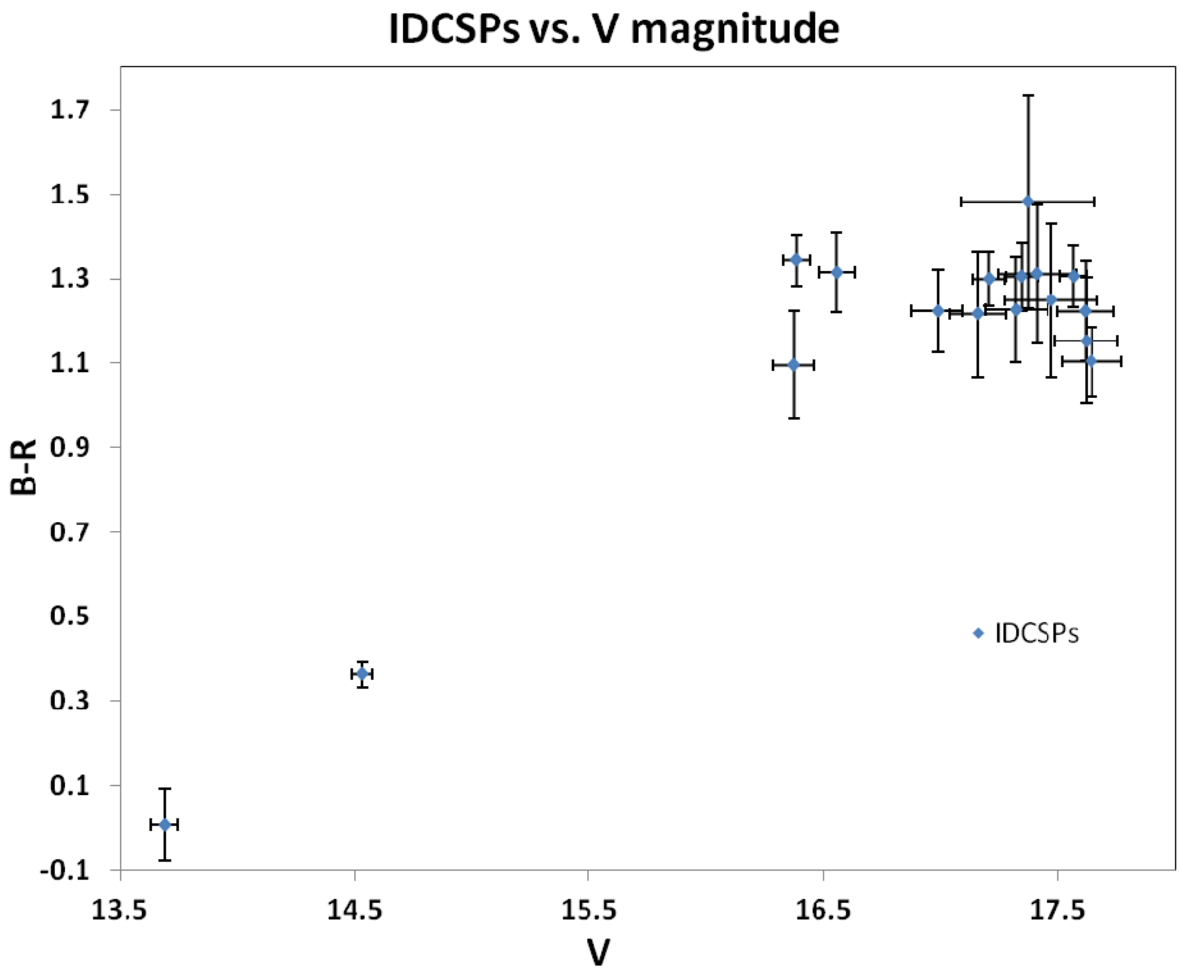

Fig. 3 B-R color versus V magnitude.

2.3 Photometric results

Laboratory measurements[4] are shown for two newer black solar cells (Spectrolab UTL and ITJ), a full UTL solar cell (solar cell + Aluminum backing – this one taken by photometry), two solar cells that are visually bluish to the naked eye (Solar Cell 1 & JPL), and a solar cell not used for spacecrafts (Non-S/C cell). The (P) denotes values obtained through filter photometry; the (S) denotes values derived from their spectra. In practical terms, signal from the spectroscopy only detects the diffuse component of the reflection whereas filter photometry is capable of detecting the diffuse and specular components within the observed signal. Thus, there can be differences in detected colors if a specular component is present. These are compared with telescopic measurements of IDCSPs.

Telescopic filter data of these IDCSPs were taken sequentially in a sequence of 10xB, 10xI, 10xV, 10xR. Thus, variability in colors (displayed as sigma in Table 1 and as error bars for IDCSPs in Fig. 2, Fig. 3) can be expected if the object displays variability in its lightcurve due to rotational effects. We do observe variability in some of our IDCSP data (indicated by larger sigma values), but not in every IDCSP (indicated by much smaller sigma values). Absolute colors with no rotational effects can only be obtained if (a) the rotational period and light curve amplitude is determined and eliminated (it is not known for IDCSPs[1]), (b) the lightcurve is flat, or (c) observations in filter pairs are taken simultaneously.

The IDCSPs cluster nicely near the flight-ready solar cells. In contrast, we show that the solar cell not used by spacecrafts is very different. To distinguish the composition of unknown targets, ideally simultaneous photometry should be collected for filter pairs. In addition, the composition would be better constrained if one could factor in the area-to-mass ratio (AMR) of the object, which could limit the number of possible target types [1].

3. SPECTROSCOPY

Telescopic spectrum of IDCSP #15 (SSN02655)
Telescope: Magellan 6.5m Clay, Las Campanas Observatory, Chile
Instrument: LDSS3: Low Dispersion Survey Spectrograph (Version 3) designed for cosmology.
Feld of View: 8.3′ diameter acquisition field of view.
Slit width: 5″
Exposure time: 30 sec/spectra.
Sampling: 2Å/pixel
Solar analog: SF1615 (James Web Space Telescope (JWST) standard)

Fig. 4 demonstrates a visible spectrum of an IDCSP (e.g. SSN02655). This was normalized by a solar analog star spectrum (JWST standard SF1516) taken under the same conditions as the IDCSP and on the same night. The resultant spectrum was then normalized to a value of 1 in the 7500-8000Å region. The laboratory spectrum was normalized by the spectrometer’s light source as well, yielding absolute reflectance (albedo), and normalized to a value of 1 at 7500 Å. This allows us to directly compare telescopic data to laboratory data.

Preliminary results from the ground-based observational data demonstrate a relatively flat visible spectrum of this satellite (Fig. 4). For comparison, laboratory spectra taken with an ASD Field Spectrometer are shown for various spacecraft solar cells (Fig. 5). The Specrolabs ITL and UTL solar cells are visually black (see e.g. Fig. 5), whereas Solar Cell JPL and Solar Cell 1 are visually bluish in color. The IDCSP most closely matches the Solar Cell 1 lab spectrum, but is not an exact match. Note that the solar cells shown in Fig. 5 were manufactured in the 1990s whereas the IDCSP solar cells were manufactured in the 1960s. As such, we do not expect an exact match to the IDCSP data.

The up-turn of the telescopic spectrum in the red end of the spectrum may be due to:

(a) contributions from the silvery sub-structure seen in Fig. 1 (perhaps an aluminum alloy)
(b) effects due to reddening from ~45 years of exposure to space,
(c) noise dominating the reddest end of the spectrum.

Aluminum begins to downturn in this region of the spectrum, so if the silvery substrate on the IDCSPs is aluminum, choice (a) is unlikely. Space-weathering could affect the glass substrate protecting the IDCSP solar cells. Namely, outgassing and contamination on the coverglass might alter the spectrum. The behavior of the plot in the red end is typical when noise begins to dominate, so choice c may also explain the data. More investigations are warranted to understand the behavior of the observed IDCSP spectrum.

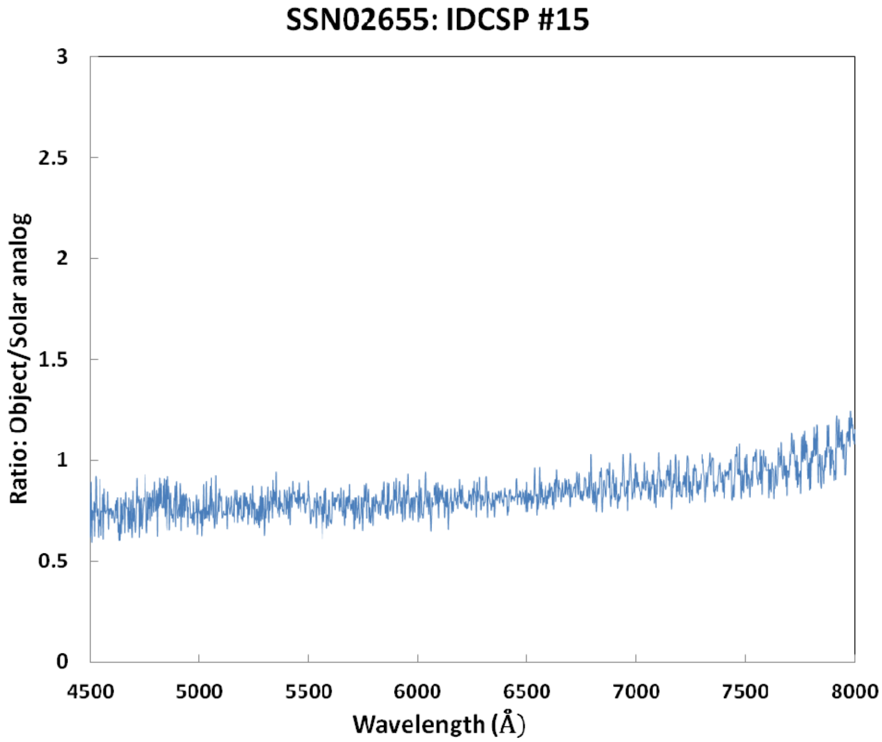

Fig. 4 Spectrum of IDCSP #15 (SSN 02655) taken with the 6.5m Magellan telescope, divided by a solar analog star. A 5″ slit was used to obtain the spectrum. The resultant spectrum is normalized in the 7500-8000Å region.

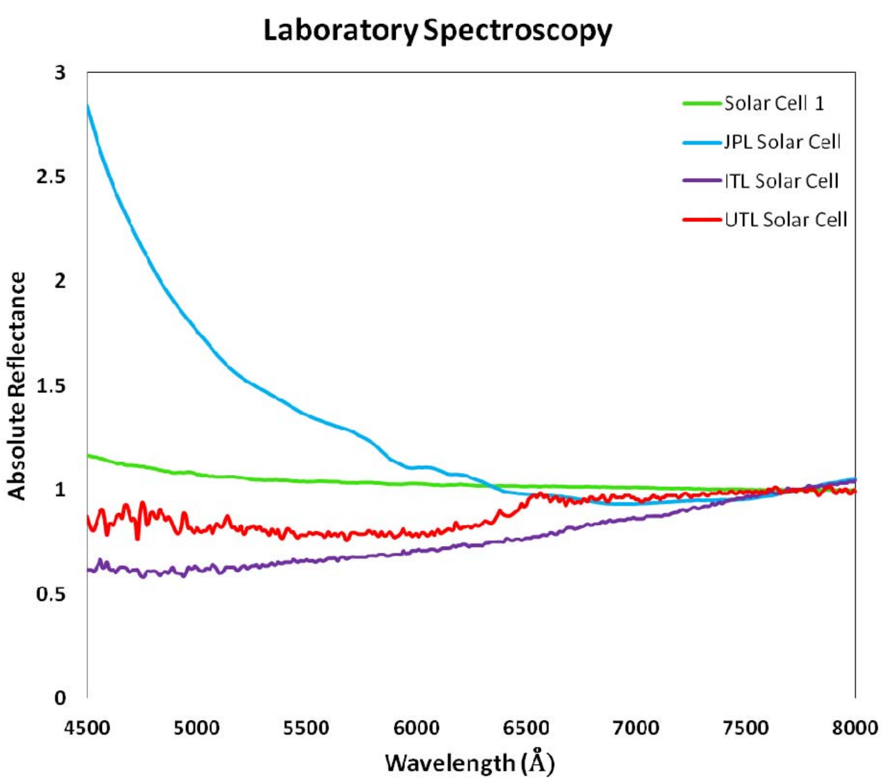

Fig. 5. Laboratory visible spectra of spacecraft materials taken with a Field Spectrometer, divided by the spectrometer's light source. The resultant spectrum is normalized at 7750Å.

4. DISCUSSION

Care must be taken in comparing photometry with spectroscopy. Most notably, Fig. 2 and Fig. 3, plot magnitudes (values decrease with increasing flux) whereas in Fig. 4 and Fig. 5, relative reflectivity is shown, which is an intensity measurement (values increase with increasing flux).

In considering the spectra of the solar cells, one should expect that the three nearly-flat spectra should cluster near each other on the color-color plot, which is observed. Given that the slopes of each of these lines are slightly different, the colors should not match exactly, which is also clear. The ITL solar cell is somewhat more reflective in R (Fig. 5) compared with the UTL cell, thus it should have a smaller magnitude in R and therefore should plot with a slightly greater B-R value, as is demonstrated in Fig. 2. The reverse is true for both solar cell 1 and the JPL solar cell: solar cell 1 has a slightly lower value of B-R, but the JPL solar panel has a much lower value as the blue portion of the spectrum is much brighter (smaller values) than R. The same exercise can be considered for the B-V values.

The difficulty is that the overall shape and colors of the three nearly-flat spectra of solar cells would make the identification based solely on the visible spectrum very difficult to distinguish between these three solar cells if the makeup of the IDCSPs were unknown. If one could obtain simultaneous photometry to ensure the resultant colors were true to the object and not affected by changes due to the rotational variability between observations, the chances of making a positive correlation between colors and material type would improve greatly. Simultaneous B and R observations have been obtained for several IDCSPs shown here. Results from these data will be presented in future work.

5. CONCLUSIONS

The spectroscopy of the IDCSP is most similar to solar cell 1; however this cell was manufactured in the 1990s whereas the IDCSPs were designed and built in the 1960s, thus an identical match is not expected. In addition, one must disentangle effects due to space weathering and the effects due to noise to aid in identification of material type and understand the cause of 'reddening' effects.

Both the photometry analyses suggests the IDCSPs material could be classified as 'solar-cell', but cannot distinguish between the three spectrally flat materials (Solar Cell 1, UTL, and ITJ) given the range of IDCSP colors. Thus, this study also demonstrates the clear benefit of taking simultaneous data in filter pairs if any rotational variation is observable to minimize the error bars and increase the likelihood of a positive identification using broadband photometry alone.

6. REFERENCES

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Preliminary Characterization of IDCSP Spacecrafts through a multi-analytical approach

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Introduction

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The targets of this study are IDCSP satellites (Initial Defense Communications Satellite Program).

Data presented here include:

(a) Visible broadband photometry (Johnson/Kron-Cousins BVRI bands) taken with the 0.9m telescope in Chile on April 19-22, 2012.
(b) Laboratory broadband photometry (Johnson/Bessel BVRI) of solar cells, obtained using the Optical Measurements Center (OMC) at NASA/JSC.
(c) Visible-band spectra taken using the Magellan 6.5m Baade Telescope at Las Campanas Observatory in Chile in May, 2012.
(d) Visible-band laboratory spectra of solar cells using an ASD Field Spectrometer.

IDCSPs

The Initial Defense Communications Satellite Program (IDCSP) was established by the United States in the mid-1960s.

- 35 satellites were launched
- First US military communications satellites placed in the GEO regime
- Emplaced in slightly sub-synchronous orbits (22.2 ±2 h) [1]
- The satellites are 26-sided polygons (86cm in diameter)
- Initially spin-stabilized
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Fig. 1:

A full-sized model of an IDCSP, on display at the Air Force Space and Missile museum in Florida, demonstrates the exterior of this satellite.

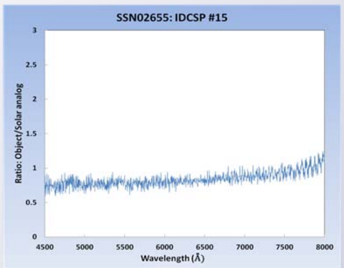

Fig. 2

Visible telescopic spectrum of IDCSP #15 (SSN 02655)[2]

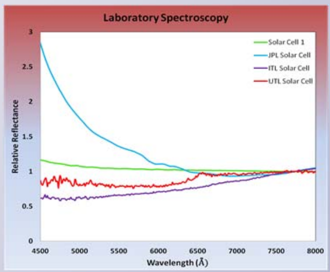

Fig. 3

Right: Visible laboratory spectra of various flight-ready Solar Cells taken with a Field spectrometer.

Spectral Analysis and Results

Telescopic spectrum of IDCSP #15 (SSN02655)
Telescope: Magellan 6.5m Clay, Las Campanas Observatory, Chile
Instrument: LDSS3: Low Dispersion Survey Spectrograph (Version 3)
Feld of View: 8.3 ′diameter acquisition field of view.
Slit width: 5″
Exposure time: 30 sec/spectra.
Sampling: 2Å/pixel
Solar analog: SF1615 (James Web Space Telescope (JWST) standard)
Phase angle at time of observation: 97°

Fig. 2 demonstrates a visible spectrum of an IDCSP (e.g. SSN02655). This was normalized by a solar analog star spectrum taken under the same conditions as the IDCSP and on the same night. The resultant spectrum was then normalized to a value of 1 in the 7500-8000Å region. Note that this telescopic spectrum is the ratio of IDCSP/solar analog whereas the lab spectrum (Fig. 3) is absolute reflectance (albedo) normalized to a value of 1 at 7500 Å. As such, one should consider the general shape of each spectrum and not the values on the y-axis.

Preliminary results from the ground-based observational data demonstrate a relatively flat visible spectrum of this satellite. For comparison, laboratory spectra taken with an ASD Field Spectrometer are shown for various spacecraft solar cells. The Specrolabs ITL and UTL solar cells are visually black (see e.g. Fig. 5), whereas the JPL and Solar Cell 1 are visually bluish in color. The IDCSP most closely matches the Solar Cell 1 lab spectrum, but is not an exact match. Note that the solar cells shown here were manufactured in the 1990s whereas the IDCSP solar cells were manufactured in the 1960s. As such, we do not expect an exact match to the IDCSP data.

The up-turn of the telescopic spectrum in the red end of the spectrum may be due to:
(a) contributions from the silvery sub-structure seen in Fig. 1 (perhaps an aluminum alloy)
(b) Space-weathering effects due to reddening from ~45 years of exposure to space,
(c) noise dominating the reddest end of the spectrum, or

Aluminum begins to downturn in this region of the spectrum, so if the silvery substrate on the IDCSPs is aluminum, choice (a) is unlikely. Space-weathering could affect the glass substrate protecting the IDCSP solar cells. Namely, outgassing and contamination on the coverglass might alter the spectrum. The behavior of the plot in the red end is typical when noise begins to dominate, so choice c may explain the data as well. More investigations are warranted to understand the behavior of the observed IDCSP spectrum.

Please see [2]Seitzer et al., this conference for further information regarding Spectral results

References:
[1]Lambert J.V., P. Sydney, J.L. Africano, V. SooHoo, K. Hamada, P.W. Kervin, E.G. Stansbery, D.L. Nishimoto, K.S. Jarvis, and M.K. Mulrooney 2001. A Search for the Lost IDCSP Constellation. 19th Space Control Conference.
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[5]Bedard D., Using a Physics-based Reflection Model to Study the Reddening Effects Observed in Spectrometric Measuremetns of Artificial Space Objects. Amos 2011.

Material	Source	B-V lab	B-V sol corr	B-R lab	B-R sol corr
Sun			*0.625*		*0.981*
UTL Solar panel	filter photometry	0.192	*0.817*	0.092	*1.070*
UTL Solar Cell	spectrum	-0.005	*0.620*	0.200	*1.178*
ITJ Solar cell	spectrum	0.073	*0.698*	0.476	*1.454*
Solar cell 1	spectrum	-0.134	*0.491*	0.023	*1.004*
Solar cell JPL	spectrum	-0.716	*-0.091*	-0.851	*0.127*
Non-S/C cell	filter photometry	0.153	*0.778*	-0.804	*0.177*

Table 1: *Photometry of laboratory samples with respective photometric color indices before solar corrections (lab) and after solar corrections (sol corr). The latter values can be compared directly with telescopic data in Table 1, and in color-color plots (See Fig. 4).*

IDCSP #	SSN	B-V wt	σ (BV)	B-Rwt	σ (BR)
1	02215	0.813	0.075	1.315	0.095
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Table 2: *Telescopic photometry of IDCSPs.*

Photometry Analysis

TELESCOPIC PHOTOMETRY of 18 IDCSPs

Telescope: CTIO 0.9m SMARTS telescope, CTIO, Chile
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Exposure times: B filter: 20 sec, VRI filters: 10 sec
Exposure sets: 10 images per filter per set, 1-3 sets taken per IDCSP
Filters: Johnson/Kron Cousins broadband filters, Blue (B), Visible (V), Red (R), and Infrared (I)

- The Image Reduction and Analysis Facility (IRAF) "*daophot*" package was used to extract photometry for all IDCSP data.
- All data were bias subtracted, flat fielded, sky subtracted, and corrected for atmospheric extinction, resulting in calibrated absolute magnitudes.
- Landolt standard star fields were used to calculate atmospheric extinction parameters.
- All colors given are weighted averages using 10 – 30 images in their respective filters, weighted by the photometric errors (e.g. uncertainties due to sky and digital imaging) of each photometric measurement.
- The standard deviations, σ(BV) and σ(BR), are estimates of the variability of the data within the set of images used to calculate the weighted average (rather than representing the photometric errors).

LABORATORY PHOTOMETRY OF SPACECRAFT MATERIALS

Laboratory: Optical Measurements Center (OMC), NASA's Orbital Debris Program Office
Setup: Analogous to a telescope set-up with a light source, target, and detector
Lightsource: 75-watt, Xenon arc lamp (simulates solar illumination from 2000 to 25000Å)
Instrument: Santa Barbara Instrument Group (SBIG) CCD camera ,1024 x 1536 pixels
Filters: Johnson/Bessel filters: Blue (B), Visible (V), Red (R), and Infrared (I)

- Laboratory colors are given with and without solar corrections. Solar corrected values are plotted below.
- Values were obtained either directly through filter photometry (BVRI filters) or derived from spectra.

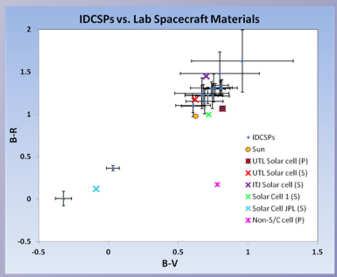

Fig. 4: *Visible photometry of telescopic and lab data: Color-color plots of IDCSPs are shown with various (solar corrected) spacecraft components. Photometry of components were taken in the Optical Measurements Center with either filter photometry (P) or derived from spectroscopy (S). (see Cowardin[3,4] for further details)*

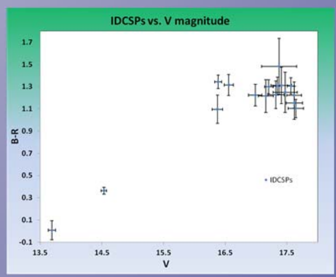

Fig. 5: *B – R color of IDCSPs with respect to V magnitude.*

Photometry Results

In Fig.4, laboratory measurements[4] are shown for a full UTL solar cell (P) (solar cell (front side) + Aluminum (back side), two newer black solar cells (Spectrolab UTL and ITJ), two solar cells that are visually bluish to the naked eye (Solar Cell 1 & JPL), and a solar cell not used for spacecrafts (Non-S/C cell). The (P) denotes values obtained through filter photometry; the (S) denotes values derived from their spectra. In practical terms, signal from the spectroscopy only detects the diffuse component of the reflection whereas filter photometry is capable of detecting the diffuse and specular components within the observed signal. Thus, there can be differences in detected colors if a specular component is present. Also, we expect slightly different B-R colors for the UTL and ITJ cells based on the spectra.

The laboratory colors are compared with telescopic measurements of IDCSPs. Telescopic filter data of these IDCSPs were taken sequentially in a sequence of 10xB, 10xI, 10xV, 10xR. Thus, variability in colors (displayed as sigma in the table and as error bars for IDCSPs in figures) can be expected if the object displays variability in its lightcurve due to rotational effects. Larger error bars indicate greater variability. Absolute colors with no rotational effects can only be obtained if (a) the rotational period is known a priori and eliminated (it is not known for IDCSPs[1]), (b) the lightcurve is flat, or (c) observations in filter pairs are taken simultaneously.

Note that in the color-color diagram, IDCSPs cluster nicely near the flight-ready solar cells. In contrast, the solar cell that is not used by spacecrafts is very different. The two outliers to this grouping are also significantly brighter in the V-band than those that are in the grouping. Future research will address the cause of this difference.

Conclusions

The spectroscopy of the IDCSP is most similar to solar cell 1; however this cell was manufactured in the 1990s whereas the IDCSPs were designed and built in the 1960s, thus an identical match is not expected. specifically, one must disentangle effects due space weathering and the effects due to noise to aid in identification of material type and understand the cause of 'reddening' effects.

Both the photometry analyses suggests the IDCSPs material could be classified as 'solar-cell', but cannot distinguish between the three spectrally flat materials (Solar Cell 1, UTL, and ITJ) given the range of IDCSP colors. Thus, this study also demonstrates the clear benefit of taking simultaneous data in filter pairs if any rotational variation is observable to minimize the error bars and increase the likelihood of a positive identification using broadband photometry alone.