REFLECTANCE SPECTRA OF SPACE DEBRIS IN GEO

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ABSTRACT

The space debris environment in the Geostationary Earth Orbit (GEO) region is mostly investigated by means of optical surveys. Such surveys revealed a considerable amount of debris in the size range of 10 centimeters to one meter. Some of these debris exhibit particularly high area-to-mass ratios as derived from the evolution of their orbits. In order to understand the nature and eventually the origin of these objects, observations allowing to derive physical characteristics like size, shape and material are required. Information on the shape and the attitude motion of a debris piece may be obtained by photometric light curves. The most promising technique to investigate the surface material properties is reflectance spectroscopy.

This paper discusses preliminary results obtained from spectrometric observations of space debris in GEO. The observations were acquired at the 1-meter ESA Space Debris Telescope (ESASDT) on Tenerife with a low-resolution spectrograph in the wavelength range of 450-960 nm. The target objects were space debris of different types with brightness as small as magnitude 15. Some simple-shaped, intact 'calibration objects' with known surface materials like the MSG-2 satellites were also observed. The spectra show shape variations expected to be caused by the different physical properties of the objects. The determination of the possible materials is still in a preliminary phase. Limitations of the acquisition process of the spectra and the subsequent analysis are discussed. Future steps planned for a better characterization of the debris from the observed data are briefly outlined.

1. INTRODUCTION

A significant population of faint debris with high area-to-mass ratios (AMR) in the range of 1 to 50 m^2/kg exists in the Geostationary Earth Orbit (GEO) region. The team of the Astronomical Institute of the University of Bern (AIUB) discovered the population several years ago using the ESA 1-meter Space Debris Telescope (ESASDT) in Tenerife and AIUB's 1-meter ZIMLAT telescope located in Zimmerwald near Bern, Switzerland [1]. Individual groups, partly in the context of internationally coordinated projects, have undertaken significant observational effort to investigate the properties of this new class of debris objects during the past years. The current consensus is that these objects may be fragments of multi-layer insulation blankets. However, this hypothesis is essentially based on the observed area-to-mass ratios only.

Currently all observations of high AMR objects are obtained by means of ground-based optical telescopes. Optical surveys provide astrometric positions and the brightness (magnitude) of the objects. The positions are used to determine and maintain the orbits of the objects and thereby to determine the AMR. Magnitudes and their variations may be used to estimate object sizes and attitude changes. The conversion of the magnitudes to physical sizes, however, requires detailed knowledge of the surface properties and the shapes of the objects (albedo, amount of specular v.s. diffuse reflection, color, etc.). Sequences of brightness measurements over time, so-called light curves, may give some indication about the objects shapes and the tumbling or rotation rates. Measurements of GEO debris objects with the ZIMLAT telescope showed a wide variety of temporal variations with time scales ranging from a fraction of a second to tens of minutes [2], [3]. Two teams reported color photometry observations of high AMR objects in GEO-like orbits [3][4]. Such observations could provide information on the surface material of the objects, however, the determination of colors proved to be difficult due to strong temporal brightness changes of the objects (the observation systems used in these studies could not measure multiple colors in parallel). Consequently the current results are not conclusive. Reflection spectra obtained with a spectrograph, on the other hand, provide a simultaneous and almost continuous measurement of the brightness of the object over a wide wavelength range. (The measurement is only "almost continuous" because each spectrograph is limited by its spectral resolution.) Reflection spectra of rocket bodies in LEO and GEO were reported by a NASA team in 2001 [5]. In the same paper the authors perform a first comparison of these spectra with spectra of material samples taken in the laboratory. Further important work on this subject can be found in [6] and [7].

In 2008 ESA initiated a study to identify, test and evaluate technologies to perform spectroscopic measurements of objects in GEO with the aim to derive physical information on the objects and to analyze whether such information is detailed enough to classify objects (satellite bus-type, fragment-type) in support of a future European Space Surveillance System. In the following we report preliminary results from observations acquired with a low-resolution spectrograph at the ESASDT.

2. OBSERVATIONAL SETUP

Spectroscopic observations were performed with a low-resolution spectrograph mounted at RC-focus of the 1-meter ESASDT telescope. The spectrograph was originally designed for observations of comets and is clearly not optimized for space debris observations. The dispersive element of this spectrograph is a transmission grating, more precisely a combination of a grating with a prism, a so-called ‘grism’ (the prism is used to bring the desired wavelength range (order) back to the optical axis). Table 1 lists the available grisms of the ESA spectrograph. The resulting spectrum is detected by a liquid nitrogen cooled 2k x 2k CCD camera.

Identifier	**Apex angle**	**Line Density**	**Material**	**Wavelength range**
GrismBB	8°	150 lines/mm	BK7	450 – 960 nm
Grism1b	26.8°	478 lines/mm	Suprasil 311	320 – 550 nm
Grism2	18.8°	222 lines/mm	BK7	500 – 1000 nm

Table 1: Grism of the ESA spectrograph.

The selection of the grism was entirely dictated by signal-to-noise considerations. The target objects were all expected to be fainter than magnitude 12, some even in the range of magnitude 16 to 17. In the case of stars or solar system objects these magnitudes would not pose any particular difficulty but merely require long exposure times of the order of several ten minutes. The maximum observation time for moving objects is much shorter and is primarily given by the density of the stellar background (at magnitudes equal or brighter than the target object): every once in a while the object ‘crosses’ a star, which will contaminate the measurement. The ‘mean free path’ for a GEO object of magnitude 17 is of the order of ten seconds only. Given these restrictions we decided to maximize the signal-to-noise ratio per pixel by using the grism with the lowest dispersion. This grism has a center wavelength of 510 nm and provides a resolution of 0.4 nm per pixel over a wavelength range from 450 to 960 nm.

Due to the broad band width of the dispersion (more than one octave) the second order gets dispersed into the same spatial area. Therefore an additional order separation filter had to be used to observe the wavelength range >500 nm, whereas the useful wavelength range without this filter is limited to wavelengths <550 nm. We used an OG515 glass filter which cuts-off wavelengths <515 nm.

The ESA spectrograph is typically used together with the ESASDT autoguider system. The autoguider redirects the light of a guide star into a dedicated high-speed camera by means of an off-axis pickup mirror. Obviously this principle is not applicable for objects with considerable angular velocities with respect to the stars. The telescope had thus to be operated in the ‘open loop’ tracking mode. From experience we knew that serious tracking errors would accumulate over short time intervals due to limitations in the mount model. Test observations indicated tracking drifts of the order of one arcsecond per minute. On average an object would therefore move out of even the largest slit within a few minutes (assuming perfect ephemerides). Unfortunately there is no possibility to observe the slit and thus the correct placement of the object in the slit during the exposure. As a consequence we decided to use the largest available slit, which is about 6 arcseconds wide.

The spectrograph is mounted on a rotation device allowing rotation of the entire focal plane assembly with respect to the telescope optical axis. This device may be used to orient the slit parallel to the atmospheric dispersion, i.e. perpendicular to the horizon, in order to prevent clipping of the dispersed object image by the slit. However, as the rotation device can only be operated manually we decided to use one orientation throughout the night.

3. OBSERVATIONS

First observations took place during 6 nights in November 2008, followed by runs of 5 nights in January 2009 and three nights in May 2009. Eventually only about half of the nights were of sufficient atmospheric quality, so-called 'photometric' nights.

The aim of our spectrophotometric observations is the quantitative measurement of the reflection properties of the target objects as a function of wavelength. It is worth noting that spectrophotometric measurements differ significantly from spectroscopic measurements of stars. The aim of the former is always a quantitative comparison of the measured spectrum with the spectrum of the illuminating source, in our case, the Sun. The calibration of the science observations should therefore ideally be done by measuring the Sun. During nighttime we have to revert to so-called 'solar analog' stars, whose spectra resemble the solar spectrum to great extent. For this calibration we have to follow similar rules as in the case of color photometry, where no calibration stars are in the field of view, i.e.

- the calibrations have to be performed immediately before and/or after the science measurement;
- the calibration stars (solar analog stars) should ideally be located near the science fields or at similar air mass as the science fields;
- the atmospheric conditions should be as good as possible, i.e. the night should be 'photometric'.

It turned out that there were only very few solar analog stars visible during a given night and they were only in rare cases located near the science field or at the same air mass. We therefore had to resort to classical methods of estimating the atmospheric extinction using the observations of the calibration stars (see Section 4).

The actual observation sequence for the moving objects was rather complicated. First the target object was acquired in the science camera with the slit and the grism moved out of the optical path. The object was then centered at the slit position and the slit inserted into the beam. After manually re-centering the object in the slit the grism was moved in and a science observation of four minutes taken immediately. The grism was moved out again and the object's position checked. If the object moved out of the slit the latter had to be moved away and the entire re-centering/exposure sequence had to be repeated. Usually four science exposures of 4 minutes each were taken in a row. These series were followed by an exposure of the spectral calibration lamp. The entire sequence was executed separately for the blue part of the spectrum (without order separation filter) and the red part (with order separation filter).

The observations of the solar analog stars were more conventional. For these objects the autoguider could be used and long exposures were possible. The blue and the red part of the spectrum were again acquired separately, followed by an exposure of the calibration lamp.

Selection of target objects

As these were the very first spectroscopic observations of GEO objects with the ESASDT they had clearly experimental character. We therefore selected some rather bright objects to start with and gradually targeted fainter objects with the goal to perhaps obtain some spectra of the brightest high AMR GEO objects at about 16th magnitude. We planned to observe four categories of objects:

1. minor planets (results to be compared with published data)
2. large intact GEO objects (catalogue objects)
3. bright GEO (small eccentricity and low AMR) or bright GTO debris objects
4. bright, high AMR GEO objects

The most important selection criterion was the availability of high quality orbits. This was particularly important for the third and fourth category. These objects were selected from AIUB's internal catalogue several weeks before the spectroscopy observation campaign and then intensively tracked by the ZIMLAT telescope in order to refine their orbits. The final selection based on orbit prediction quality and visibility was done in the day before the observation night. There was also a series of additional criteria like brightness, visibility constraints (phase angle, Earth shadow, Milky Way, etc.). For the large intact GEO objects we preferred satellites were manufactures data could be made available.

Table 2 gives the list of objects observed in the November 2008, January 2009 and May 2009 observation runs. Artemis and the two MSG satellites were chosen because manufacturer data would be available to ESA.

Object	Mag	Orbit	AMR [m^2/kg]	Object Class
01029A (Artemis)		GEO		2
02040B (MSG2)	15	GEO		2
05049B (MSG1)	15	GEO		2
s92008	12.7±1.5	GTO	0.02	3
E08211A	12.8±1.3	GEO	0.04	3
s95081	12.9±1.1	GEO	0.02	3
s95311	13.0±1.6	GEO	0.03	3
E08152A	13.1±1.0	eGEO	0.05	3
s92005	13.4±1.2	GTO	0.02	3
s90032	14.0±0.8	GEO	0.01	3
E04015A	14.2±1.1	GEO	0.2	3
s90118	15.6±0.4	GEO	13.2	4
E06321D	16.0±0.6	eGEO	2.4	4
E06293A	16.2±0.7	eGEO	15.6	4
E08159C	16.8±0.8	eGEO	11.6	4
Minor Planets				
Pomona	11.2	helioc.		1
Harmonia	9.5	helioc.		1
Solar Analogs				
SA 93-101	9.7			
SAO 93936	8.1			
…				

Table 2: List of objects observed in the November 2008, January 2009 and May 2009 observation runs. The magnitude variations in the second column are one sigma values derived from light curves and long term monitoring. 'eGEO' denotes 'elliptical' GEOs with semimajor axes around 42'000 km but eccentricities >0.1.

4. DATA REDUCTION AND RESULTS

Standard data reduction procedures were applied to obtain wavelength-calibrated spectra. The slit spectroscopy packages within the MIDAS data analysis software was used to eliminate cosmic ray events from the raw frames, subtract the sky background, bin the two-dimensional spectra into one-dimensional 'scans' and finally calibrate the dispersion using the calibration lamp exposures. After this step, the series of multiple observations of the same object (or calibration star) taken within a short time interval were stacked together. At this stage the spectra are still affected by the wavelength-dependent atmospheric extinction. If a spectrum of a solar analog star with the same extinction (i.e. at the same air mass) was available, we could simply divide the object spectrum by the solar analog spectrum to obtain the reflectivity of the target object as a function of wavelength. However, a calibration star at the same air mass was seldom available. We applied three different approaches to cope with the extinction:

1. An extinction curve was derived from all observations of solar analog stars of a particular night. This curve was then used to correct the spectrum of a calibration star – observed at possibly similar air mass as the target object – to the air mass of the target object. The target object spectrum was then divided by the corrected calibration star spectrum.
2. The program object and the solar analog star – again, preferentially one at similar air mass as the program object – were both extinction corrected to zero air mass by means of a standard extinction curve before taking the ratio.
3. In rare cases where the difference in air mass between a program object and a calibration star was minor, the two uncorrected spectra were divided directly.

Finally the blue and the red reflection spectra of an object were merged and normalized to unity at 550 nm.

Figure 1 shows spectra of solar analog stars at different air mass, demonstrating the importance of the extinction correction.

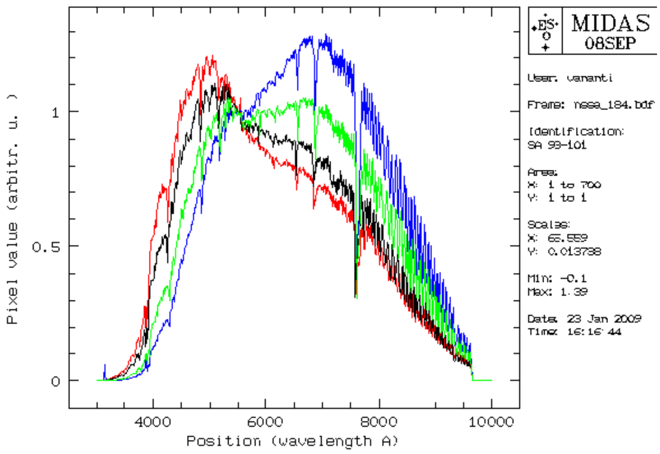

Figure 1: Spectra of solar analog stars at different air mass. The red, black green and blue curves are spectra obtained at 1.01, 1.13, 1.4 and 1.94 air mass, respectively.

Reflectance spectra of MSG-2 for different phase angles are given in Figure 2. These spectra were reduced using method 1 for the extinction correction and are low-pass filtered to remove fringing effects on the red part of the spectrum. MSG-2 shows a rather constant positive slope over the entire spectrum (the peak at ~930 nm is an artifact of the smoothing process). The slope seems to be depending on the phase angle. At high phase angles the spectrum shows a negative slope at the blue end from ~400 to 450 nm.

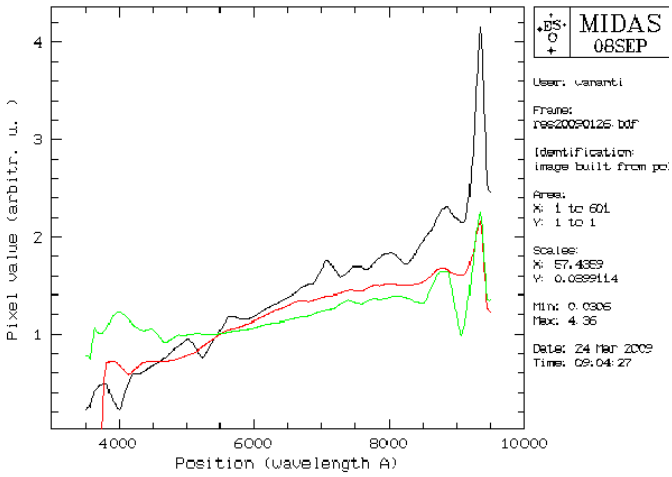

Figure 2: Reflectance spectra of MSG-2 (Cospar 02040B) at different phase angles: the black, red, and green curves are spectra at 38°, 60°, and 88° phase angle, respectively.

The following examples of reflectance spectra were all reduced by applying the above-mentioned method 2, or 3. Spectra of two rather bright GTO debris objects are shown in Figure 3. The red and the blue lines show data taken on 20090527 and 20090528, respectively. All spectra show more or less pronounced interference fringes for wavelengths larger than about 750 nm. These fringes are present in both, the target object and the solar analog spectra, but vary with time and thus cancel more or less when dividing the object by the calibration star spectra. The spectra of s92008 have a positive slope for wavelengths of 500 nm and larger, and a slight increase of the reflectance from 500 nm towards the blue end. Object s92005 shows a similar behavior, but a much stronger increase of the reflectance at the blue end. The differences between the spectra of the two nights are most likely real and not due to calibration uncertainties (all four spectra were taken at low air mass of 1.1).

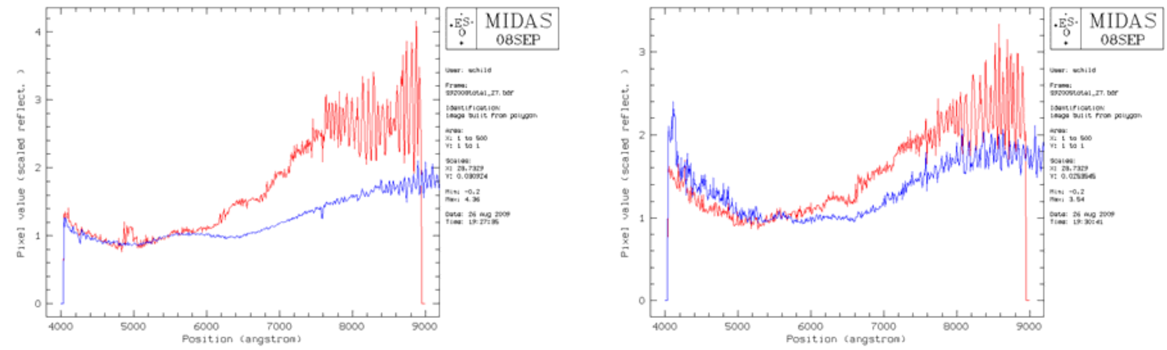

Figure 3: Reflectance spectra of two bright GTO debris objects. Left: s92008 (mag=12.7±1.5, AMR=0.02 m^2/kg); right: s92005 (mag=13.4±1.2, AMR=0.02 m^2/kg). The red and the blue lines show data taken on 20090527 and 20090528, respectively.

Reflectance spectra of the bright (13.1±1.0 mag), low AMR (0.02 m^2/kg), 'eccentric GEO' object E08152A are given in Figure 4. The reflectance has a minimum at about 650 nm and increases considerably to both, the blue and the red end. Figure 5 gives reflectance spectra of two faint 'eccentric GEO' objects with high AMR. These spectra are noisier than the previous ones as both objects are more than three magnitudes fainter. The spectrum of E08159C is similar to the ones of E08152A in Figure 4. E06293A shows a rather flat spectrum with a slight negative slope.

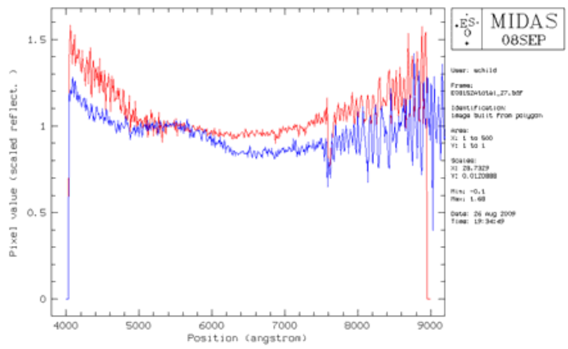

Figure 4: Reflectance spectra of the bright, low AMR, 'eccentric GEO' object E08152A (mag=13.1±1.0, AMR=0.02 m^2/kg). The red and the blue lines refer to data taken on 20090527 and 20090528, respectively.

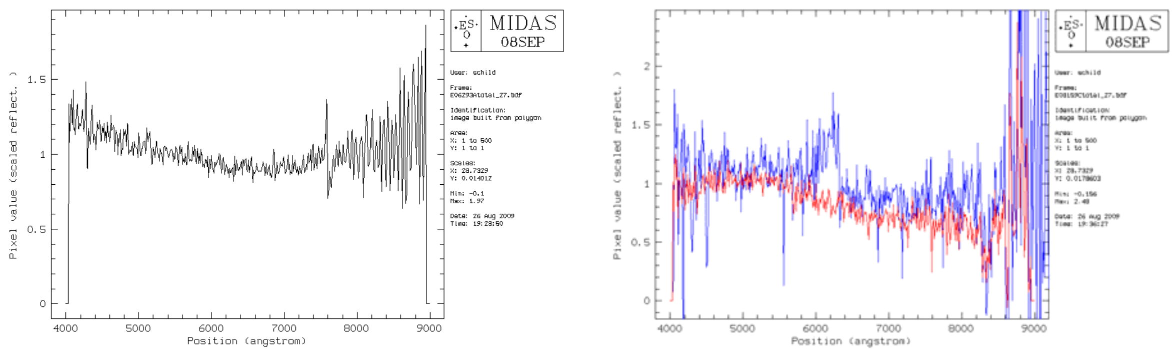

Figure 5: Reflectance spectra of two faint 'eccentric GEO' objects with high AMR. Left: E06293A (mag=16.8±0.8, AMR=11.6 m^2/kg); right: E08159C (mag=16.2±0.7, AMR=15.6 m^2/kg). The red and the blue lines in the figure at right show data taken on 20090527 and 20090528, respectively.

Given the differences seen for the spectra of the same object taken at different nights and, or phase angles it is certainly premature to conclude anything about potential materials of the object surfaces. We therefore leave it to the reader to compare the spectra of the space objects with the spectra of the following laboratory samples. Figure 6 shows laboratory spectra of two solar cell samples taken with an Oceanoptics USB2000+ spectrometer and Figure 7 gives spectra of two different multi-layer insulation materials.

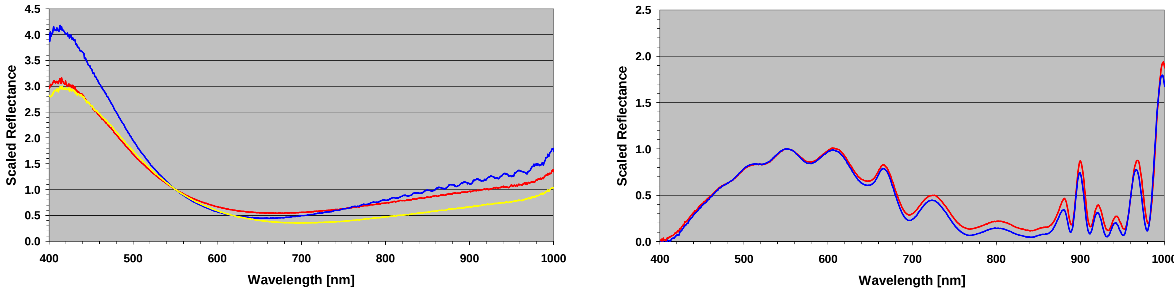

Figure 6: Reflectance spectra of two laboratory samples of solar cells. Left: solar cell sample from the Hubble space telescope solar array retrieved in March 2009 (~8.25 years in space); right: triple junction solar cell sample.

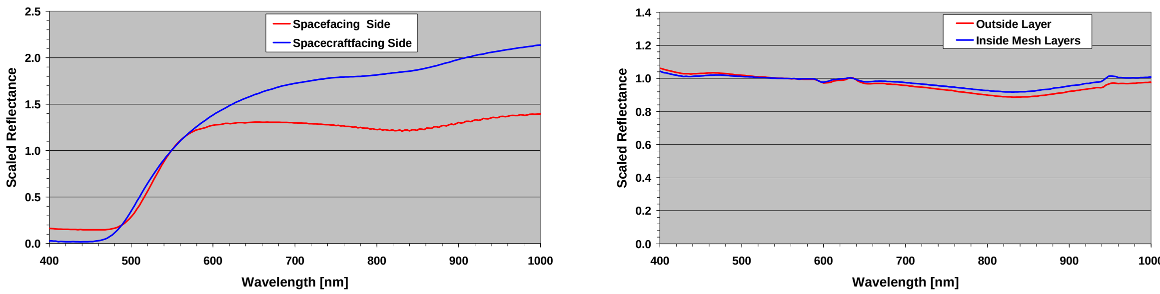

Figure 7: Reflectance spectra of 'gold' Kapton (left) and 'silver' (right) multi-layer insulation material (data provided by K. Abercromby).

5. SUMMARY AND CONCLUSIONS

Since the detection of small-size debris at high altitudes and especially the discovery of high AMR debris in GEO-like, but eccentric orbits, the main question about the nature and, equally important, their origin persists. One important observational technique to derive the material composition of the surfaces of these debris objects is optical reflectance spectroscopy.

The ESA low-resolution spectrograph at the ESASDT in Tenerife was used to obtain reflection spectra of objects in high-altitude orbits. The observations had strictly experimental character and were originally aimed to obtaining spectra of bright targets only. Eventually more than 15 different objects in GEO, 'eccentric GEO' and GTO orbits were observed. Among these observations there are the first published spectra of four faint high AMR objects.

The correction of the atmospheric extinction is the dominating error source in the data reduction. Care has to be taken that the observation nights are 'photometric' and that enough observations of solar analog calibration stars, well distributed in air mass, are acquired. Three different approaches to correct the extinctions were used. A comparison of the methods is still to be done but first analysis shows encouraging consistency.

For large, intact, attitude controlled spacecraft like MSG-2 the spectra from different night are consistent, but show dependence from the phase angle. Small debris objects show considerable variation from night to night, but the overall shape of the spectrum seem to be conserved and could thus be used to derive surface materials.

Some reflection spectra of different solar cell samples have been measured in the laboratory. Given this very limited sample and the variations observed for the individual objects it is certainly premature to draw any definite conclusions about potential materials of the object surfaces.

6. ACKNOWLEDGMENTS

The ESA observations were acquired under ESA/ESOC contracts 21447/08/F/MOS. The HST solar cell sample was provided by G. Drolshagen (ESTEC), the triple-junction solar cell sample by F. Pirgentili (La Sapienza), and the multi-layer insulation material data by K. Abercromby. The collaboration with the Keldysh Institute of Applied Mathematics (KIAM) and the ISON was instrumental in maintaining the orbits of the targeted debris objects (s92005 and s92008 were actually discovered by KIAM/ISON). The authors would like to thank J. Kuusela and D. Abreu for mounting the spectrograph and taking the observations.

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