ArgusE: Design and development of a micro-spectrometer used for remote Earth and atmospheric observations

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ABSTRACT

In this paper the design and development of the ArgusE is discussed. The ArgusE is a micro-spectrometer which has been developed for Earth and atmospheric monitoring purposes. The project is primarily focused on using the ArgusE micro-spectrometer in order to ascertain whether it is possible to obtain surface soil moisture content measurements from space using its short-wave infrared detector. The secondary objective of the project is to quantify greenhouse gases that could be studied within new spectral range.

The ArgusE is built on Argus 1000 micro-spectrometer design and spaceflight heritage. Currently, on the CanX-2 mission launched in 2008, the Argus 1000 micro-spectrometer observes the infrared solar radiation reflected by Earth surface targets as small as 1.5 km^2 and the atmosphere (aerosols, clouds, and constituents). Over the past five years that Argus 1000 has been in operation, we have accumulated more than 200 observations from a series of land and ocean targets. It was followed by the SRMSAT, launched in 2011 (India). Currently all space-based Argus 1000s are collecting Earth and atmospheric observation data within the 900 to 1700 nm spectral range, with special focus on CO_2 and other greenhouse gases, and cloud and coastline detection.

GENSPECT, a line-by-line radiative Matlab-based toolbox is used to calculate gas absorption and emissivity for a custom grouping of atmospheric gases. Given gas types and amounts, temperature, pressure, path length and frequency range for an atmosphere or laboratory cell, GENSPECT computes the spectral characteristics of the gas mixture. The resulting models used to discover the potential monitoring of atmospheric greenhouse gases and topical soil moisture content will be discussed and displayed graphically.

In addition, this paper will showcase the chassis redesign and change of electronics which allow the ArgusE to now showcase the spectral region of 1700 to 2200 nm. It will also discuss the laboratory experimental procedures of the new instrument calibration and spectral collection of soil moisture, and will present a study surrounding a potential for a new chassis material to homopolymer acetal Delrin (150 SA). The results of ASTM-E 595 Outgassing Test are discussed.

1. INTRODUCTION AND MOTIVATION

This work was performed as part of a larger Canadian Space Agency funded project. The main purpose of this project was to accurately determine whether soil moisture content could be measured from space. In order for this to be done, first atmospheric modeling was performed in order to determine where atmospheric windows exist in the new spectrometer spectral range, and redesigns were performed on the Argus 1000 micro-spectrometer in order to measure the new wavelength region. The homopolymer Delrin (150 SA) was also studied and an outgassing test performed on it in order to understand whether or not it could be used as a possible casing material for the new spectrometer. Two versions of the ArgusE micro-spectrometer were to be built, each using a different chassis material (Delrin 150 SA and Al-6061). It was to be determined if the Delrin chassis can indeed be used in space or if it is to be redefined as UAV grade only.

2. GENSPECT

GENSPECT is a spectral modeling tool used in atmospheric, climate and environmental studies [1]. Using GENSPECT, an atmospheric model will be created in order to see if a spectral window exists within the infrared spectrum where an instrument could take ground measurements without atmospheric interference. Wavelength regions which can be used for atmospheric constituent's column measurement will be noted. The GENSPECT tool allows for user input in order to create a synthetic spectrum to suit ones needs. For this project, the parameters used were reflective of data previously gathered using the Argus 1000 aboard CanX-2. The wavelength region of 1700 to 2200 nm was examined.

2.1 Geo-Parameters

The Zenith viewing angle was assumed to be zero in order to mimic a nadir viewing geometry, which is what would be accomplished when performing measurements from satellite orbiting the Earth. For surface parameters, the surface was set as smooth with a reflectance of 0.3, which corresponds to the value for wet soil [2]. The surface was chosen to be smooth in order to mimic the surface reflecting all incident energy that it receives from the sun. The other input variables set are incident angle and reflected angle, assumed each to be zero, Earth surface temperature set to 300K, and solar temperature set to 6000K.

2.2 Atmospheric Constituents

The main constituents taken into account for the GENSPECT Atmospheric model are $\mathrm{CO}, \mathrm{CO_2}, \mathrm{N_2O}, \mathrm{CH_4}, \mathrm{O_2}, \mathrm{O_3}$, and $\mathrm{H_2O}$. These constituents were chosen as infrared photons are most absorbed by these molecules and to suit the research purpose of measurement through the atmosphere in the infrared region [3]. Each atmospheric constituent was checked for any measured changes in their mixing ration levels. This was done as the mixing ratios used in GENSPECT reflected those published in 1995. Only one constituent value has changed enough to warrant a value change in the mixing ratio – $\mathrm{CO_2}$. According to Dr. Pieter Tans [4], $\mathrm{CO_2}$ has risen from 351 ppm in 1995 to 398 ppm in 2013. A new atmospheric mixing ratio file was created to reflect concentration changes. The code was modified so that all of the isotopes of each atmospheric constituent are shown. This was done in order to simulate a realistic atmosphere.

2.3 Preliminary Model Outputs

The GENSPECT program was run in order to observe the individual behaviors of each atmospheric constituent and their overall combination. First a general model reflecting the near-infrared spectrum was produced in order to see the main areas where atmospheric interference occurs.

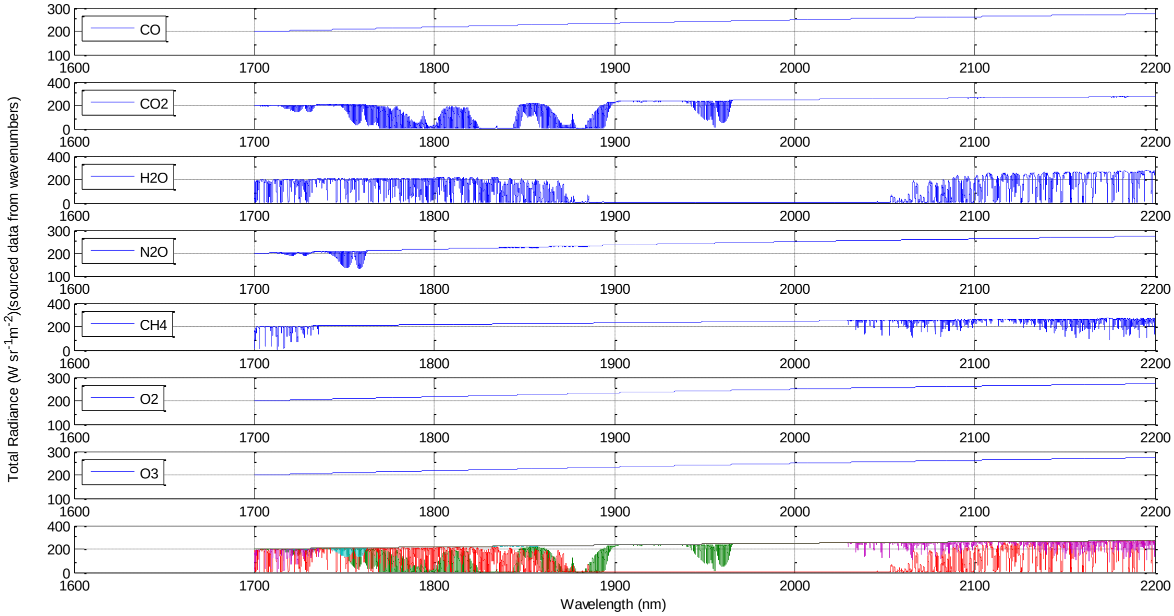


Fig. 1. All Constituents

Fig. 1 showcases the synthetic spectra of each individual constituents produced by the GENSPECT software. The y-axis represents the total radiance (W*Sr^{-1}*m^{-2}), calculated from wavenumber data, while the x-axis is the wavelength showcased in nanometers. The lowest plot shows the total combined synthetic spectrum which is expected to be observed from space. The linear regions seen in the spectral graphs showcase where zero atmospheric interference are observed. The regions where atmospheric interference occur are visible and are represented by the dark regions which travel downwards from the radiance line in the y-axis. Any region which travels downwards from the radiance line is not usable for remote infrared measurements. Fig. 2 shows a more detailed view of the total combined synthetic spectrum.

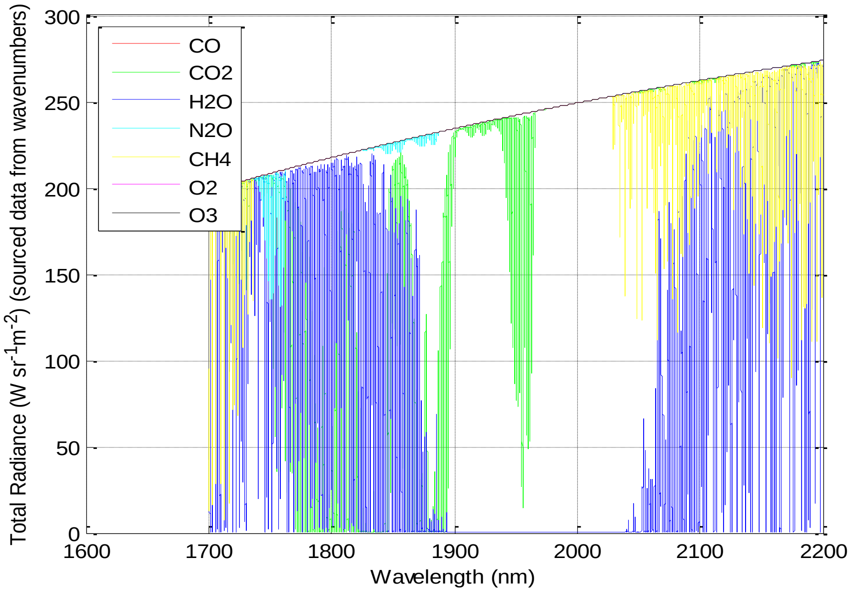


Fig. 2. Total Combined Synthetic Spectrum

The region of 1965 and 2020 nm wavelengths showcases a potential area for Earth based observations. The ArgusE spectrometer that will be used for the laboratory experiments has a 5 nm pixel resolution, allowing for multiple pixel measurements to be made between 1965 and 2020 nm wavelengths. This helps to provide a better idea of a small spectral window that may be useful towards the remote sensing of soil moisture. The Short Wave Infrared Region (SWIR) corresponds to the area which is known to contain soil health information, including soil moisture content [5]. From Fig. 2, it is evident that certain regions of the spectrum can be made to take column measurements, specifically CO_2 and H_2O.

3. ArgusE

3.1 Argus 1000

The Argus 1000 instrument is a near infrared (NIR) grating spectrometer, measuring spectra from 900 to 1700 nm. The Argus instrument has flown aboard CanX-2 since 2008 [6] and has been used to study various atmospheric constituents. At 228 g and a spectral resolution of 6 nm, the Argus is a great instrument to use for space based spectral measurements [7]. Currently the Argus 1000 spectrometer has features seen in Table 1.

Table 1. Argus 1000 Spectrometer Specifications [adapted from 7]

Argus 1000 Spectrometer Specifications	
Optics	Grating Spectrometer
Configuration	Single Aperture
Field of View	2.18 mRad viewing angle around centered camera bore-sight with 15mm fore-optics
Mass	228 g
Accommodations	40 mm x 50 mm x 80 mm
Operating Temperature	-20 to +40
Survival Temperature	-25 to +50
Detector	265 element InGaAs Linear Array
Grating	300 grooves/mm plane grating (12mm x 12mm)
Spectral Resolution	6 nm
Operational Modes	1: Continuous cycle, constant integration time 2: Continuous cycle, adaptive exposure 3: Single shot
Data Delivery	Fixed length parity striped packets of single or co-added spectra with sequence number, temperature, array temperature, and operation parameters.
Integration Time	500 µs to 4.096 s
Calibration	Five-wavelength laser calibration and radiance calibration
Volatiles	Less than 0.1% volatile internals by mass.
Exposure Environment	Clean-room class 10,000 or better recommended. Class 1,000 required for optical or internal inspection.
Signal to Noise Ratio	120:1
Dark Noise	11 RMS counts
Power Consumption	2.4 W (max)

For the new spectral range of 1700 to 2200 nm to be observed, a modified version of the Thoth Technology micro-spectrometer Argus 1000 was designed and built. The component changes that were to the made to the instrument in order to maximize the measurement of soil moisture content in the SWIR region.

3.1 InGaAs Linear Array

Linear arrays are linear focal planes that are composed of individual detectors. The InGaAs linear array is a specific type of array mean to detect light in three specific IR ranges 900 to 1700 nm, 1100 to 2200 nm or 1100 to 2600 nm. There are many other options such as detector height, pixel pitch and the number of pixels in the array to consider when choosing a linear focal plane array.

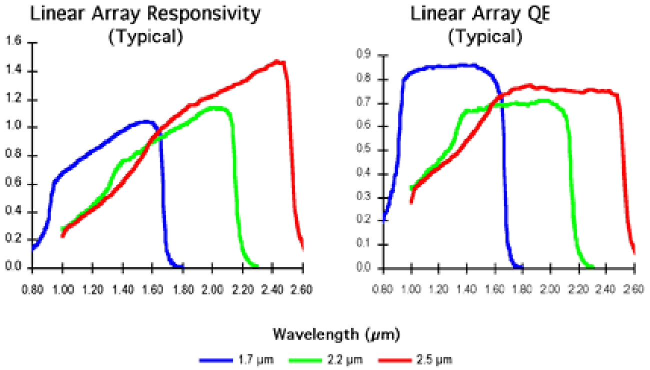
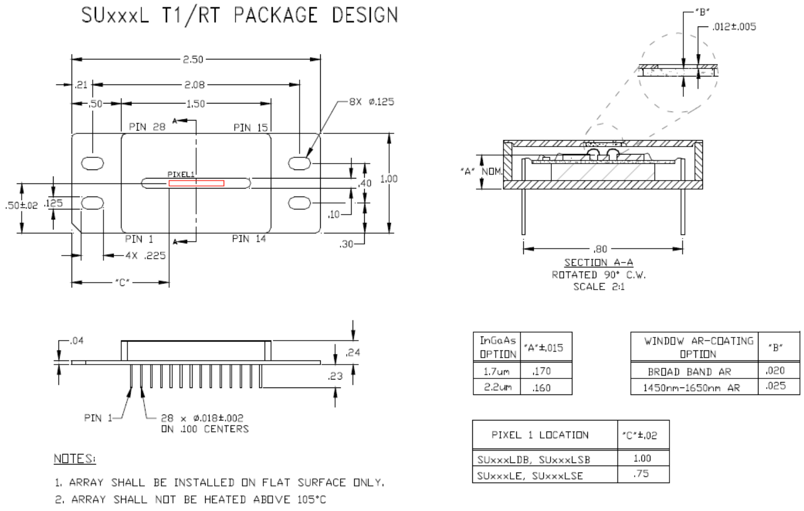


Fig. 3. Responsivity and QE of Linear Arrays [http://www.sensorsinc.com/arrays.html]

The Quantum Efficiency and Responsivity of the linear arrays varies according to the spectral sensitivity of the linear plane array. The Responsivity of the linear plane array increases in values from the start of the spectral range to the end of it, whereas the QE is mainly stable in the spectral region of interest. The new spectral range that the ArgusE will measure has a Responsivity of 0.9 to 1.1 from while the QE is found to be 0.65 to 0.7 in the spectral range 1700 nm to just below 2200 nm.

The design goals of the ArgusE were to mimic the optical and electrical systems of the Argus 1000. In order to do this, each system was revamped. The current InGaAs Linear Array model used for the Argus 1000 was studied and compared to the LSB model which came recommended by Sensors Unlimited, Inc. The SU256LSB-2.2TI-0250 InGaAs linear array is considered to be state of the art technology and is currently available on the market, featuring the latest technology in one- stage TEC cooling. When comparing the spectral sensitivity, number of pixels and pixel height and pitch, both the current model and LSB are the same. The SU256LSB-2.2T1-0250 was chosen due to availability and better cooling system which has a chance to result in better data collection. The physical length of the detector in this chip measures to 12.5 mm, which is used in order to solve for the new optical design. The sizing of the SU256LSB-2.2T1-0250 array is seen in Fig.4.



InGaAs OPTION	"A"±.015
1.7um	.170
2.2um	.160

WINDOW AR-COATING OPTION	"B"
BROAD BAND AR	.020
1450nm-1650nm AR	.025

PIXEL 1 LOCATION	"C"±.02
SUxxxLDB, SUxxxLSB	1.00
SUxxxLE, SUxxxLSE	.75

NOTES:

1. ARRAY SHALL BE INSTALLED ON FLAT SURFACE ONLY.
2. ARRAY SHALL NOT BE HEATED ABOVE 105°C

Fig. 4. SU256LSB-2.2T1-0250 Sizing

3.3 Chassis Redesign

The chassis required enlargement in order for the new electronics deck and internal optical components. This gave space for more stable mounts to be placed internally. The optical deck which shields the optical components was changed in order to contain the new pathways the light-waves travel. Additional mounting holes were also added in the optical deck in order for either the redesigned electronics deck. The CAD models for both the Argus 1000 and ArgusE instrumentation are shown. Fig. 5 shows a typical optical deck mounted over the regions where light sensitive equipment is mounted, while in Fig. 6 the grating and detector mounting equipment can be seen. The location to each mount is specifically determined for the spectrometer's end use (desired spectral range) and will vary with instrument to instrument.

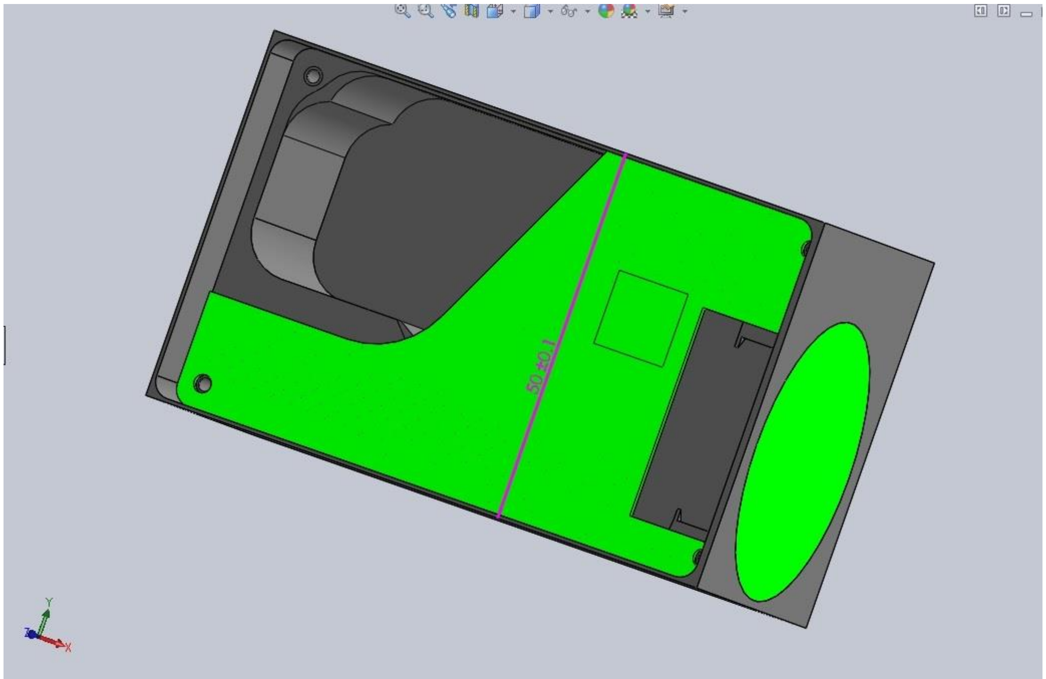


Fig. 5. Argus 1000 CAD model

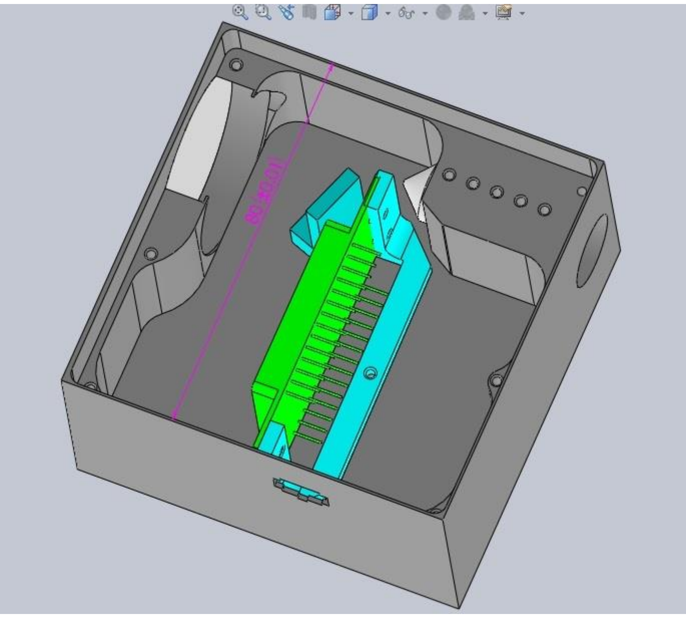


Fig. 6. ArgusE CAD Model

In order to accommodate for the new desired spectral range, the ArgusE instrument chassis was enlarged from 40 mm x 50 mm x 80 mm [7] to 80 mm x 50 mm x 80 mm. The final assembled ArgusE can be seen in Fig. 7. The final weights for the assembled chassis' are 206.48 g for the Al-6061 assembly and 116.37 g for the Delrin 150SA version.

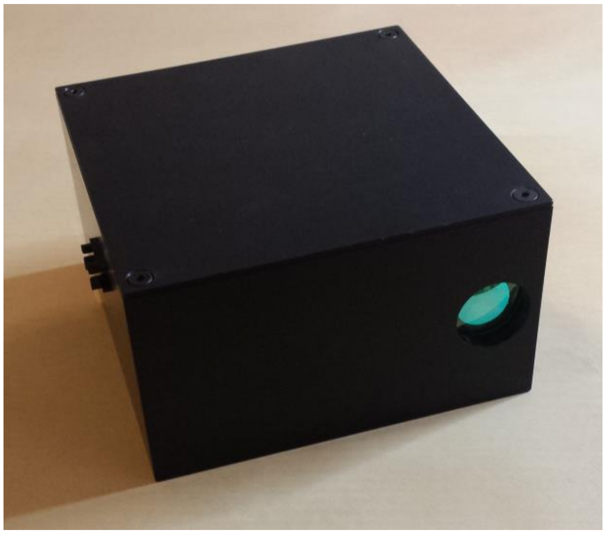


Fig. 7. Assembled ArgusE micro-spectrometer

4. DELRIN

Chassis material is very important when designing a spectrometer. This is the material responsible for ensuring that the internal electrical and optical components are stable and unmoving during the spectrometer use. If there is internal movement, then the spectrometer will not function as planned and the spectral data retrieved may be useless. For the ArgusE model, the use of Delrin was studied. Delrin is a homopolymer acetal which shows a good balance of internal properties meant to bridge the gap between plastics and metals. Delrin is typically manufactured by DuPont [8]. Many types of Delrin are available for purchase which comes in a variety of processing methods and product characteristics. All DuPont manufactured Delrin products show good dimensional stability, have good wear and abrasion properties, are chemically resistant to hydrocarbons, solvents and neutral chemicals, resulting in a product which can be used for many industrial applications. For this project, the types of Delrin available needed to be narrowed down. Delrin can be processed using both extrusion methods and injection molding. Only Delrin grades that were processed using extrusion methods were looked at, as they are more densely packed and found to exhibit maximum toughness versus the injection molded Delrin. Only three types of Delrin are manufactured using extrusion methods. They are seen in Table 2.

Table 2. Composition of Delrin Acetal Resins [8]

Delrin Grade	**Process Characteristics**	**Product Characteristics**	**Applications**
150SA	High viscosity resin with low die deposit.	Maximum toughness in an extrusion resin without modification.	Highly stressed sheet, rod and tubing.
150E	High viscosity resin with low die deposit.	Toughness with reduced center-line porosity.	Exclusively stock shapes that is greater than .25 inches thick.
550SA	General purpose extrusion resin with additive system that allows fast cycling without voids or warpage.	Excellent balanced properties in resin producing uniform rod stock.	Stock shapes for machining part, including rod, sheet, and tube.

From the properties compared in Table 2, Delrin 150SA is the type of Delrin grade chosen to build the ArgusE chassis. The material currently used for the Argus 1000 spectrometer is AL-6061. The shortened table of material characteristics is seen in Table 3.

Table 3. Al-6061 and Delrin 150SA Material Properties [8, 9]

Properties		**Al-6061**	**Delrin 150SA**
Physical	Density (g/cc)	2.7	1.41
Mechanical	Ultimate Tensile Strength (MPa)	310	101
	Shear Strength (MPa)	207	66
	Poisson Ratio	.33	.35
	Modulus of Elasticity (Young’s Modulus) (GPa)	69	3.103
Thermal	Thermal Conductivity (W/mK)	167	.4

Table 3 showcases the potential downfall’s for Delrin 150SA’s use in space. Mainly its thermal conductivity is low enough that additional systems would be needed in order to ensure the heat produced by the Argus electronics board were to be drawn sufficiently away.

4.1 ASTM E 595 Total Mass Loss and Collected Volatile Materials from Outgassing in a Vacuum Environment

The industry standard test for measuring outgassing in materials is ASTM (American Society for Testing and Materials) E 595. Developed by NASA [10] to screen low outgassing materials for use in space, the test determines the volatile content of material samples placed in a heated vacuum chamber. It measures the Total Mass Loss (TML), Collected Volatile Condensable Material (CVCM) and Water Vapor Regained (WVR).

The main equipment used at Thoth Technology to perform this test is the TVAC, thermal vacuum, chamber. The chamber is used normally to test macro-items, but can be used to testing of micro-quantities. The chamber is equipped with various types of thermocouples in order to ensure the desired temperature is reached inside of the chamber.

The testing was performed in from Feb. 27th 2015 to March 2nd 2015 using the measurements methods and apparatus’ described in ASTM E 595-98. Multiple numbers of samples were being tested during this time in the TVAC. Each sample must be between 100 and 300 milligrams of mass and is placed into a pre-weighed aluminum foil boat, which has been cleaned and dried. The samples are then bathed in a 24-hour pre-conditioning soak at 25 °C, 50% relative humidity and standard atmospheric pressure to ensure that the samples receive a common preliminary treatment. Following the bath, the individual samples are re-weighed then placed into individual compartments in a solid copper bar which can be heated. Each compartment is closed by a solid copper cover, requiring that all volatile materials escape only through a 6.3-mm (0.25-in.) diameter exit port.

The Delrin 150SA samples (Fig. 8.) are approximately 5.25+/-.01 mm in dimension, each weighing in the region of 202 milligrams.

Fig. 8. Delrin (150SA) Samples Prepared for ASTM E 595 Test

The copper heater bar is heated to 125° C for 24 hours. The sample is also heated to 125° C by conduction and radiation. This causes the volatile materials to be driven off, with their only escape being through the exit port. At a distance of 12.7 mm, a chromium-plated collector is in direct line of sight of the exit port and is maintained at 25° C. The majority of escaping volatiles collect on the chromium-plated disk while barriers near the collector plate to prevent cross-contamination between neighboring samples.

The TML is determined from the weights measured pre and post the 125° C soak in vacuum and is presented as a percentage loss, while similarly the weight differences between the cleaned collector and that of the collector with condensed outgassed materials on it is used to observe the mass of the condensables and is calculated as a percentage of the starting mass of the sample (CVCM). The final value measured is the WVR which is a percentage of the starting mass of the amount of water reabsorbed in 24 hours while the sample is exposed to 25° C, and 50-percent relative humidity bath.

Table 4. Delrin 150SA Data

Parameter	**Unit**	**Test Data**	**Test Data**
Test Manager	#	RJ	RJ
Start Date	#	27-Feb-15	27-Feb-15
End Date		02-Mar-15	02-Mar-15
Client ID	#	cat1	cat2
Thoth ID	#	P-002	Q-002
Description	#	Delrin Cube 1	Delrin Cube 2
Manufacturer	#	DuPont	DuPont
Requestor	#	Tsouvaltsidis	Tsouvaltsidis
Sample Temperature	C	125	125
Collector Temperature	C	25	25
Pressure	Torr	1.0E-05	1.0E-05
Time at temperature	hours	24	24
Number of samples per boat	#	1	1
Approx. weight per sample	g	0.202984	0.202424
Position number	#	P	Q
Initial holder mass	g	0.061136	0.068514
Final holder mass	g	0.061118	0.068586
Initial collector mass	g	16.823192	16.655632
Cleaned Collector Mass	g	16.823246	16.655574
Final collector mass	g	16.823294	16.655680
Position number	#	P	Q
Initial holder + sample	g	0.264072	0.270872
Initial + sample after 24hrs	g	0.264094	0.270888
Final holder + sample	g	0.263228	0.270024
Reweighed sample + holder	24 h 50% RH	0.263426	0.270224
Initial collector mass	g	16.823246	16.655574
Final collector mass	g	16.823294	16.655680
Total Mass Loss (TML)	%	0.43%	0.43%
Total Mass Gain (CVCM)	%	0.02%	0.05%
Total Water Regained (WVR)	%	0.10%	0.10%

Materials pass or fail the test based on these TML and CVCM measurements. If the CVCM exceeds 0.1%, the material fails. The material will also fail if the TML exceeds 1%—though the TML may be offset by water vapor regained (WVR) by the sample in a subsequent measurement [12]. The conditions which need to be met are seen in Table 5.

Table 5. ASTM E 595 Pass/Fail Conditions

Condition		**Outcome**
CVCM	**TML**	
< 0.1%	<1%	Material passes
<0.1%	>1%	If TML-WVR <1%, material can pass
> 0.1%		If TML-WVR > 1%, material fails

If a material passes NASA low outgassing tests, it can potentially be used in a multitude of applications including outer space, high vacuum, specialty optical and electro-optical applications, among others.

5. INSTRUMENT CALIBRATION

In order to perform a thorough analysis and interpretation, all the acquired spectral data should be converted to the corresponding radiance per wavelength values. This conversion can be carried out once the calibration of ArgusE is performed. The calibration process, which involves in using a light source, spectralon, and the ArgusE spectrometer, plays a key role in converting the instrument detector array measurements into radiance values. A halogen lamp source is utilized to validate the test procedure and the process is repeated using another calibrated light source to minimize error in the calibration. The calibration methodology for Argus is based on the method being followed and provided in Tsouvaltsidis [13] where an Argus 1000 instrument was calibrated in lab.

Figure 7 illustrates the laboratory set up for the calibration process which involves in the halogen lamp, spectralon, and Argus spectrometer. The blackbody radiation emitted by the halogen lamp reflects off the spectralon into the spectrometer.

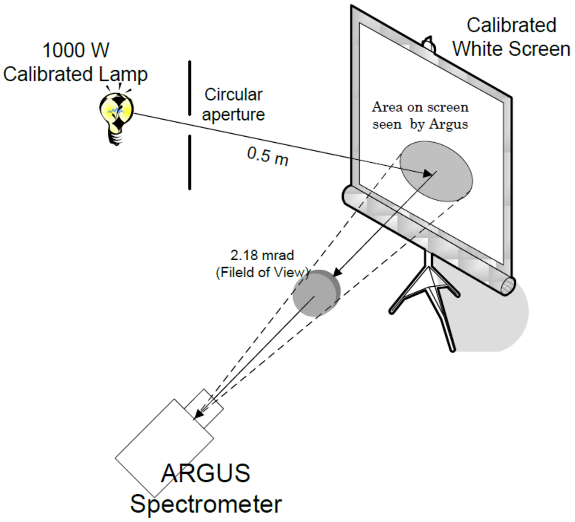


Figure 7. Block diagram for radiance calibration [14]

The spectral emittance of the halogen is a function of wavelength λ, and temperature T, and is given by

$$E_{ph\lambda f}(\lambda,T) = \varepsilon(\lambda,T)\cdot\frac{2\pi c}{\lambda^4}\cdot\frac{1}{e^{\frac{hc}{\lambda kT}}-1} \qquad (1)$$

where ε = emissivity of the halogen filament
c = speed of light
h = Planck constant
k =Boltzmann's constant

The wavelength range of the spectrometer is known from the wavelength calibration experiment and converts the pixel numbers on the spectrometer to wavelength values. The spectral emittance can be calculated at each wavelength using this conversion and can then be used to determine the brightness of the spectralon screen. This is done using the following equation:

$$B_{ph\lambda f}(\lambda, T) = a_f \cdot E_{ph\lambda f}(\lambda, T) \cdot \alpha(\lambda) \cdot \frac{1}{L^2} \cdot \frac{1}{4\pi^2} \cdot \cos\theta \qquad (2)$$

where a_f = halogen lamp emitting area
α = screen albedo
L = lamp to the screen distance,
θ = angle between the lamp and the spectrometer.

The power, P, received by the instrument at each wavelength can then be calculated using Equation 3.

$$P = B_w \varphi \pi \left(\frac{D}{2}\right)^2 \qquad (3)$$

where ϕ = spectrometer field of view spectrometer
D = spectrometer lens diameter

The amount of energy per count, JPC, can then be determined using the Equation 4.

$$JPC = \frac{Pt}{N} \qquad (4)$$

where t = exposure time setting of the instrument
N = number of detector counts at each wavelength

6. CONCLUSIONS

The synthetic spectrum was generated using GENSPECT. From this, a probable atmospheric window looks to exist in the SWIR region from 1965 to 2020 nm. The potential for atmospheric column measurements to be taken were assessed and perceivably CO_2 and the H_2O columns can be measured.

The ArgusE micro-spectrometer built with both chassis materials (AL-6061 chassis and Delrin 150SA). The traditional chassis performed as expected during assembly, while the Delrin (150SA) chassis outperformed in terms of relative strength while being flexed. ASTM E 595 testing was performed on the Delrin material used for the ArgusE chassis. Delrin 150 SA by definition passed the testing.

During the calibration process, the energy per count relationship solved for using ArgusE.

7. FUTURE WORK

Future work includes performing controlled laboratory experiments in order to see if a correlation between radiance observed at 1965 and 2180 nm exists with varying soil moisture content. The use of Delrin must be further studied in order to understand if the most modern versions of 150SA are suitable for space. This includes further thermal cycling in a vacuum chamber, bombardment with ozone particulates and vibration testing to ensure material solidity while comparing all results with those known for AL-6061. This will help to determine is the Delrin chassis can indeed be used in space or if it is to be redefined as UAV grade only.

8. ACKNOWLEDGMENTS

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