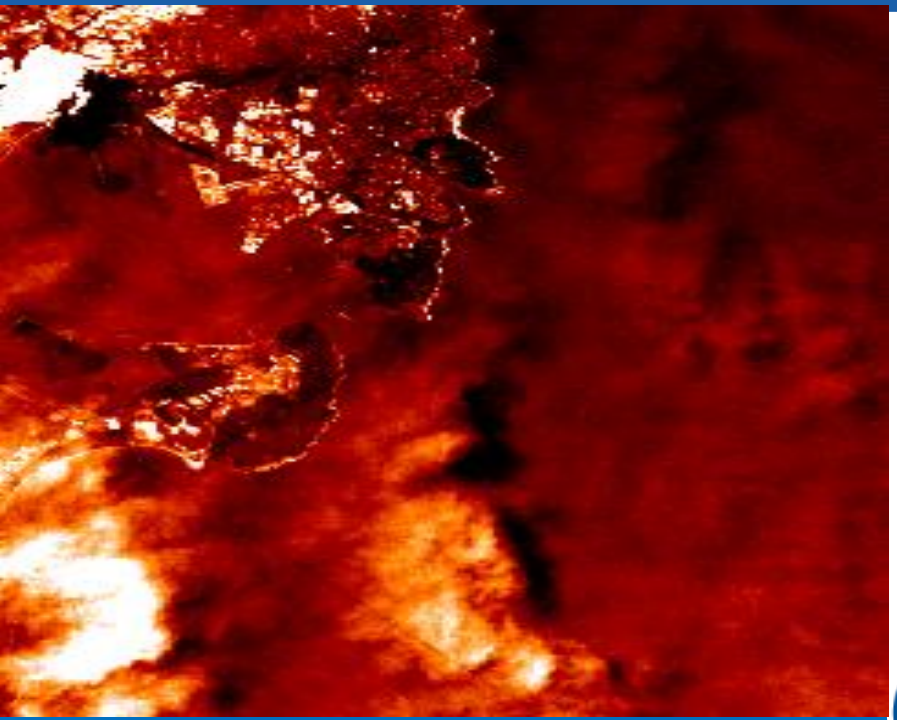
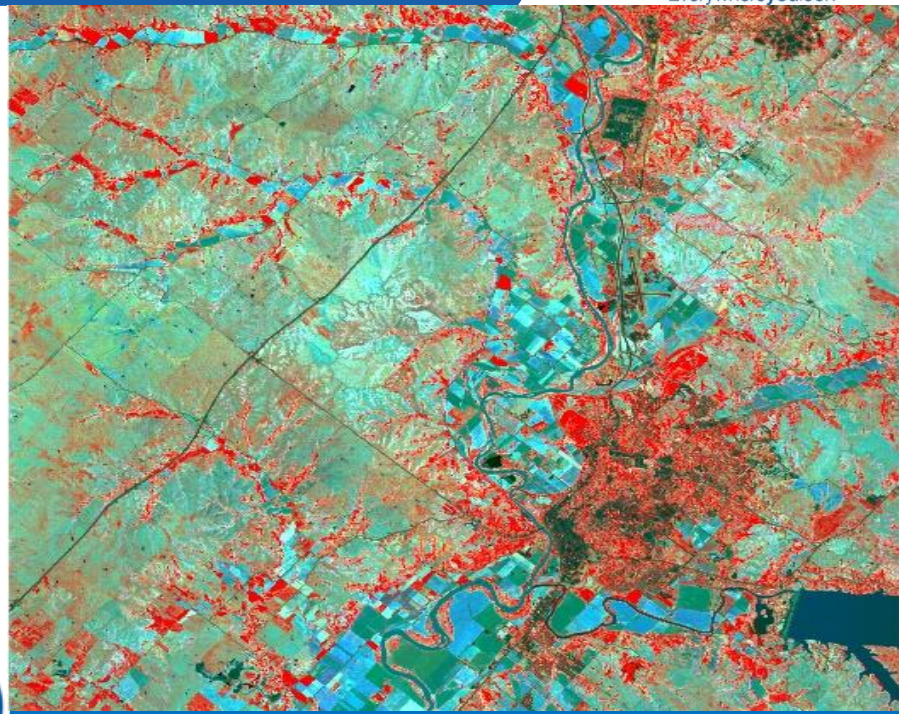




NASA Brown Bag on DESIS Imagery

Kara Burch, Amanda O'Connor, Yvonne Ivey

April 9th, 2020

Agenda

1. Introduction to the DESIS Team
2. MUSES Platform
3. DESIS Hyperspectral Imager
4. DESIS Data Products
5. On-Orbit Performance, Calibration, Validation
6. DESIS Hyperspectral Imagery Catalog
7. DESIS Applications
8. Resources
9. Questions / Answers / Next Steps

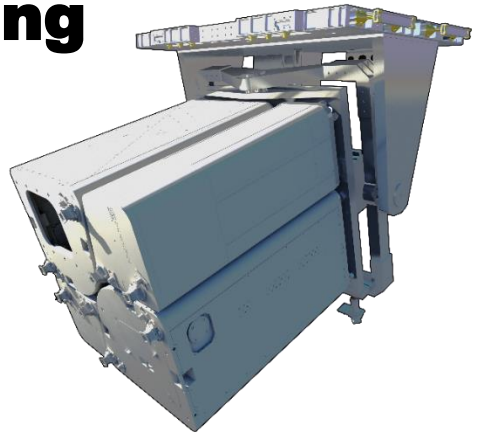
DESIS Team

- Jack Ickes, Teledyne Brown Engineering
  Senior Vice President, Geospatial Solutions
  Program Manager
- Yvonne Ivey, Booz Allen Hamilton
  Earth Science Data System Program
  NASA POC for DESIS data
- Kara Burch, Innovative Imaging and Research (I2R)
  Senior Scientist
  Technical POC: Image Quality & Instrument Performance
- Amanda O'Connor, Teledyne Brown Engineering
  Commercial Director, Geospatial Solutions
  Hyperspectral Phenomenologist
- Heath Lester, Teledyne Brown Engineering
  Operations Manager
  Acquisition Coordinator

MUSES PLATFORM

TELEDYNE BROWN ENGINEERING Everywhereyoulook™

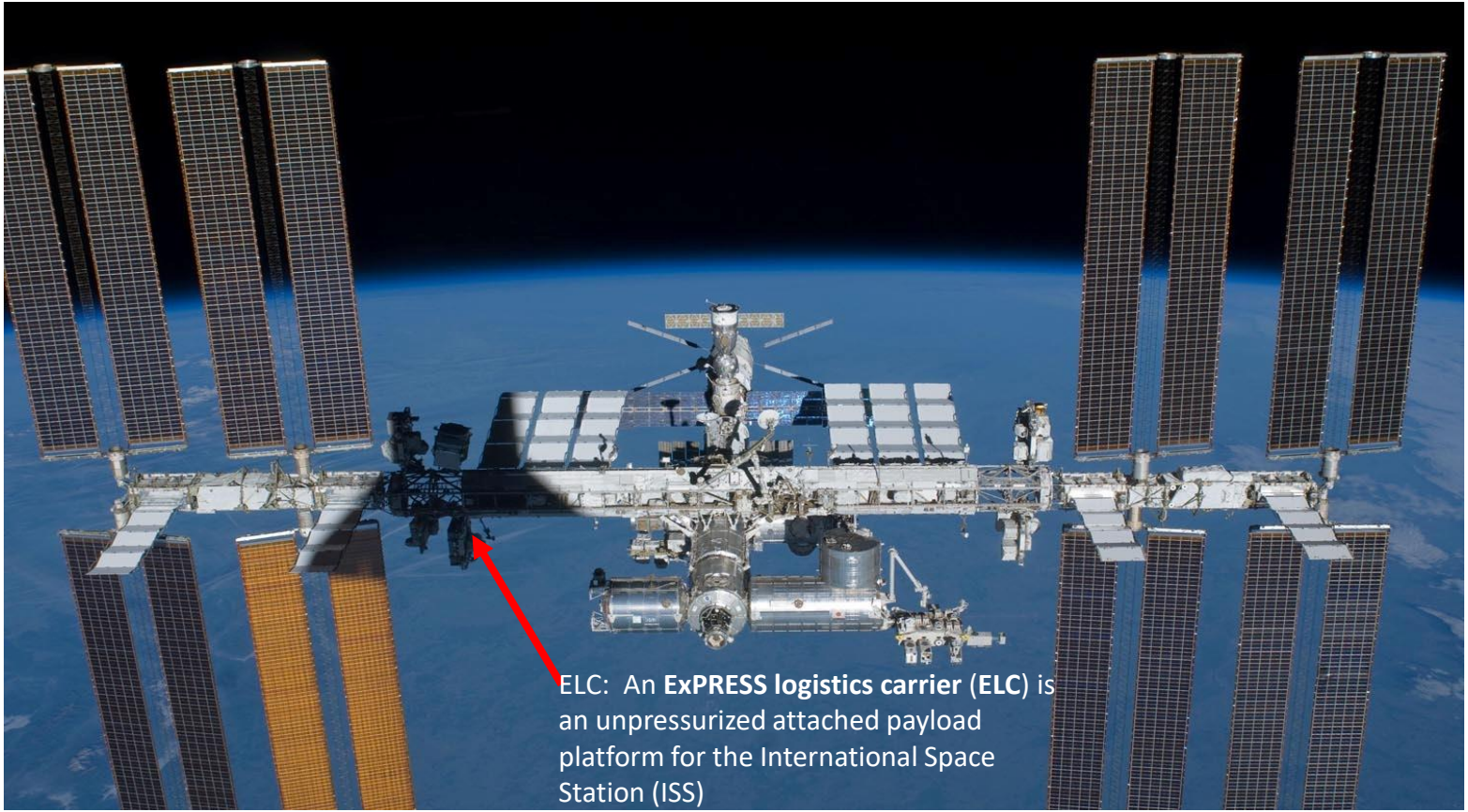
Multi-User System for Earth Sensing (MUSES)



- Precision Pointing Platform, designed in cooperation with NASA, for low-cost earth observation from the International Space Station (ISS).
- Up to 4 robotically installed instruments. Payload can be removed and returned to earth for analysis or reuse.
- Total data downlink ~225 GB/day.
- Onboard processing option.
- < 12 Months: Contract to Launch.
- ~ 1/3 the cost of a free-flyer mission.

Characteristic	MUSES Performance Target
Field of Regard	Outboard Cross-Track: 5°
	Inboard Cross-Track: 45°
	Along-Track: +/- 25°
Thermal Control	Passive
Star Tracker	Sodern SED26
Inertial Measurement Unit	Honeywell Miniature Inertial Measurement Unit (MIMU)
Precision Time	Sourced from the ISS GPS, ≤ ± 250 µsec to MUSES instruments
Pointing Accuracy	≤ ± 60 arc seconds
Pointing Knowledge	≤ ± 30 arc seconds (~ 60 m on ground from 400 km altitude)
Location knowledge	Sourced from the ISS GPS, ± 50 meters, RMS
Orbit	51.6° Inclination, 400 km altitude ± 5% (nominal)
Data Processing	Linux Server on-board ISS with redundant 6 TB storage
Daily Downlink Capacity	225 GB

MUSES/DESIS Location on the ISS Express Logistics Carrier 4 (ELC-4)



Earth Observation From the ISS – Why It Works/Challenges

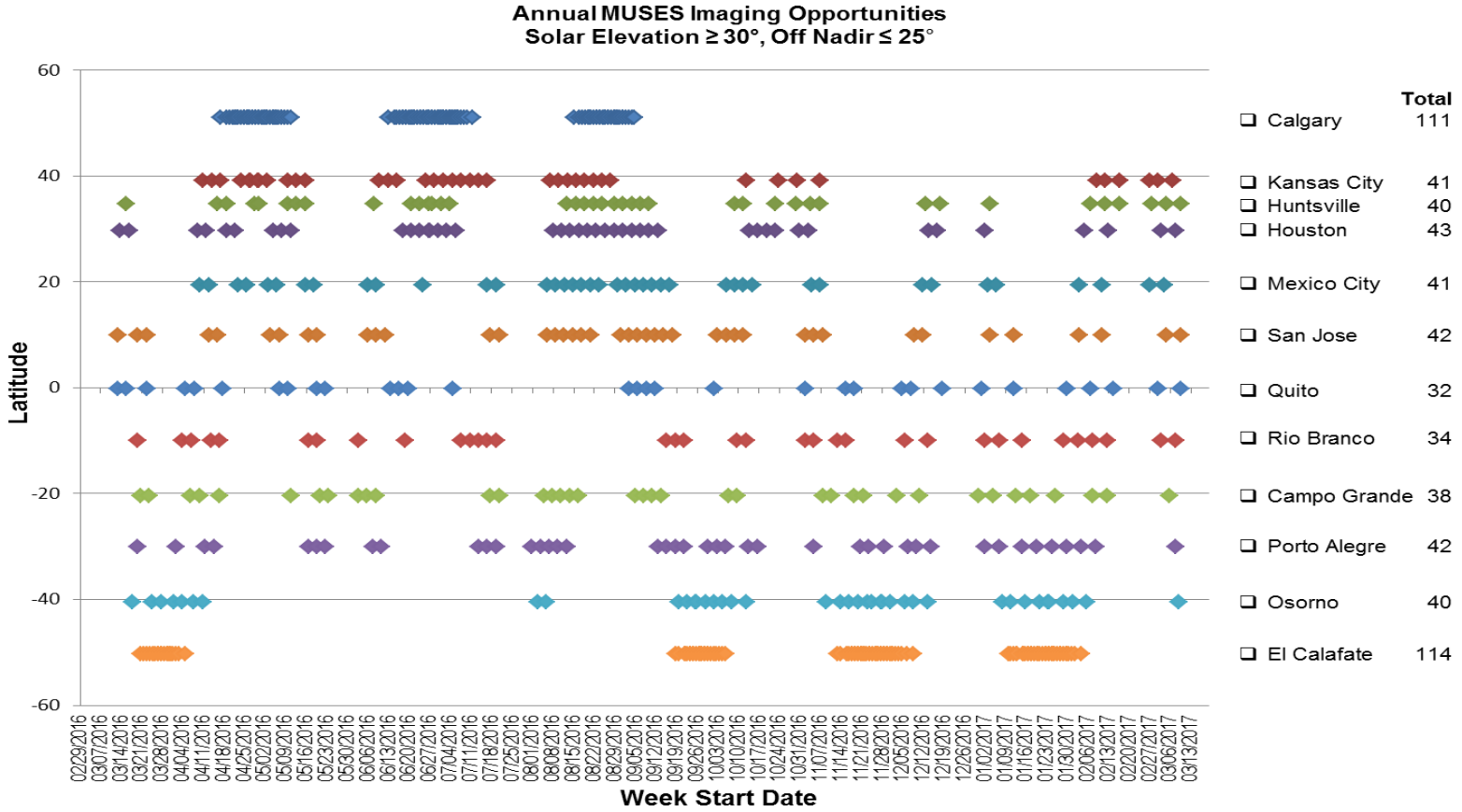
Benefits

- Coverage of ~90% of populated Earth
- Coverage of tropics, frequent revisit times off-noon allow for reduced-cloud image acquisition.
- Orbit enables acquisitions at different times of day, useful for BRDF or diurnal dynamics.
- Upgrade, repair and exchange of instruments as technology and/or markets evolution. Traditional barriers to entry are minimized.

Challenges

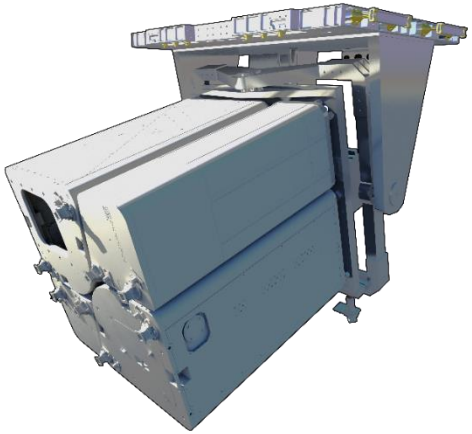
- Above 55^{o} N and below 52^{o} S not covered in orbit.
- Revisit time has a beat frequency that depends on latitude.

MUSES Imaging Opportunities from the ISS

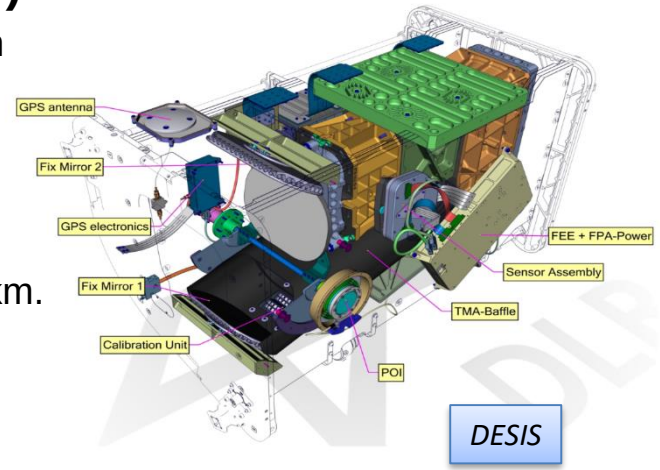


DESIS
Hyperspectral Imager

DESIS Overview



- **Cooperative effort between the German Aerospace Center (DLR) and Teledyne Brown Engineering (TBE)**
  - MUSES first payload – Launched June of 2018.
  - Teledyne has commercial rights to imagery while DLR retains the rights for scientific use.
- **DLR Earth Sensing Imaging Spectrometer (DESIS)**
  - 235 bands with 2.55 nm sampling over the VNIR spectral region (400-1000 nm)
  - 30 m GSD @ ISS 400 km orbit.
  - Sensor pointing ±15° along track, enables BRDF and stereo acquisitions.
  - Push Broom Sensor: Maximum length of a single strip ~ 3000 km.
  - Each strip is broken into 1024 x 1024 pixel tiles, or 30 x 30 km.



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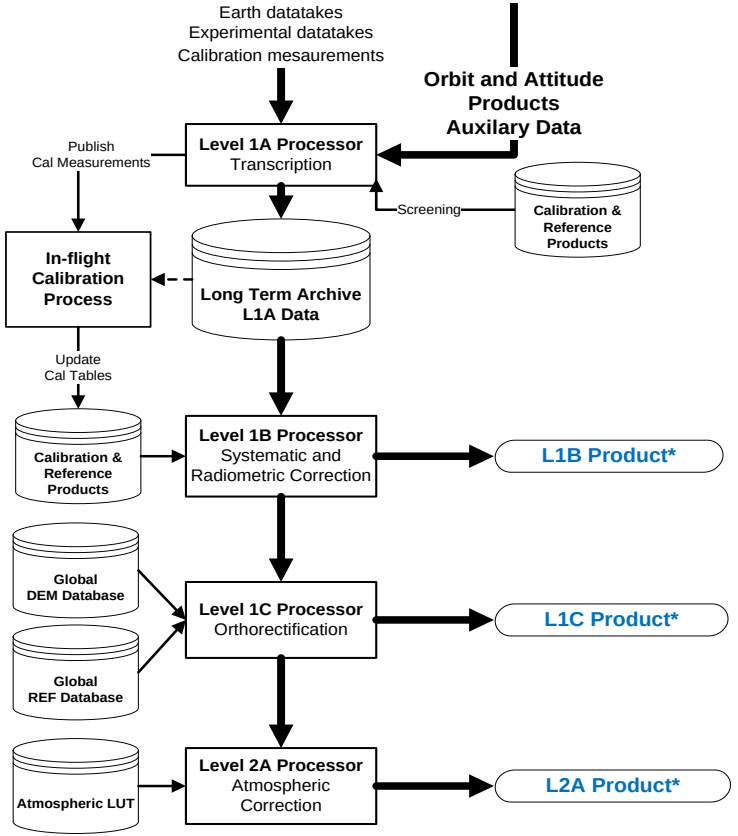
DESIS Specifications

Parameter	DESIS Specification (Commissioning Phase)
Orbit	not Sun-synchronous, 51.6°, 400 ± 5 km, 93 min, no repeat cycle
Coverage	55° N to 52° S
Tilt (across-track, along-track)	+45° to -5°, -40° to +40° by MUSES and DESIS
Sensor Pointing	±15° along-track to enable BRDF or Stereo acquisitions
Spectral coverage	402 nm to 1000 nm (Part of FPA defective at low wavelengths)
Number of spectral channels	235 (no binning); 118 (binning 2); 79 (binning 3); 60 (binning 4)
Spectral Sampling resolution	2.55 nm (w/o binning); ~10.2 nm (binning 4)
Full Width Half Maximum (FWHM)	~3.5 nm (w/o binning); ~10.5 nm (binning 4)
Radiometric resolution	12 bits + 1 bit gain
Radiometric Accuracy	±10% (based on on-ground calibration and with support of inflight radiometric calibration; Expect ±5%)
Radiometric Linearity	99%
Swath	30 km
Spatial resolution, pixels	30 m, 1024 pixels (@400 km)
Geometric accuracy	~20 m with GCPs ~300 m - 400 m w/o GCPs (i.e. water only collects)
MTF @ Nyquist	30%-40% based on on-ground calibration / static MTF without smearing effects / wavelength depending
Signal-to-Noise ratio (albedo 0.3 @ 550 nm)	195 (w/o binning) 386 (4 binning)
Solar zenith angle restrictions (for L2A level processing)	> 55° produces reduced quality L2A product > 65° produces low quality L2A product > 70° not processible to L2A

DESIS
Data Products

Product Overview

- **DESIS L1A raw data stored in archive.**
  - Not an available product.
- **Several levels of processing available for end-users.**
  - L1B Radiance
  - L1C Orthorectified Radiance
  - L2A Surface Reflectance
- **Processing applied on-the-fly in the online archive when data is ordered.**



*Delivery product

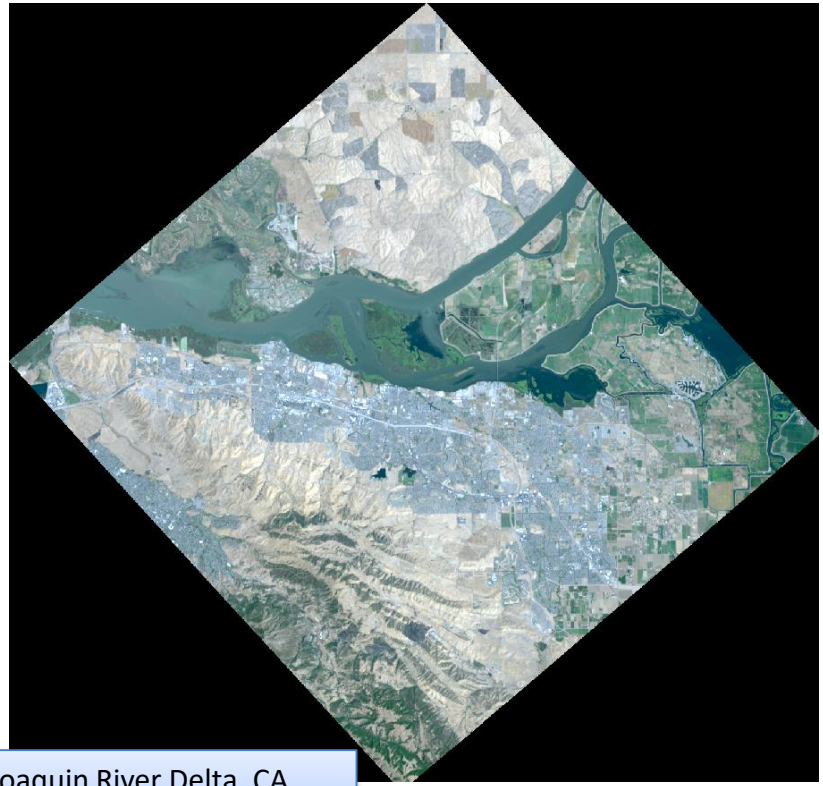
L1B Radiance

- **Top-of-Atmosphere (TOA) Radiance product (L1B)**
  - Radiometric corrections applied: non-linearity, dark current, and radiometric conversion.
  - Sensor corrections applied: defect pixel, rolling shutter, spectral smile and striping.
- **Quality information included identifies suspect pixel values.**

San Joaquin River Delta, CA
August 14, 2019 @ 17:50 GMT

L1C Orthorectified Radiance

- **Orthorectified TOA Radiance product (L1C)**
  - Sensor distortion removed.
  - On-the-fly image matching using high geometric accuracy reference images to extract ground control points (GCP).
  - When image matching not possible, correction consists of on-board position/attitude, and estimated boresight angles.
- **Quality information included identifies suspect pixel values**

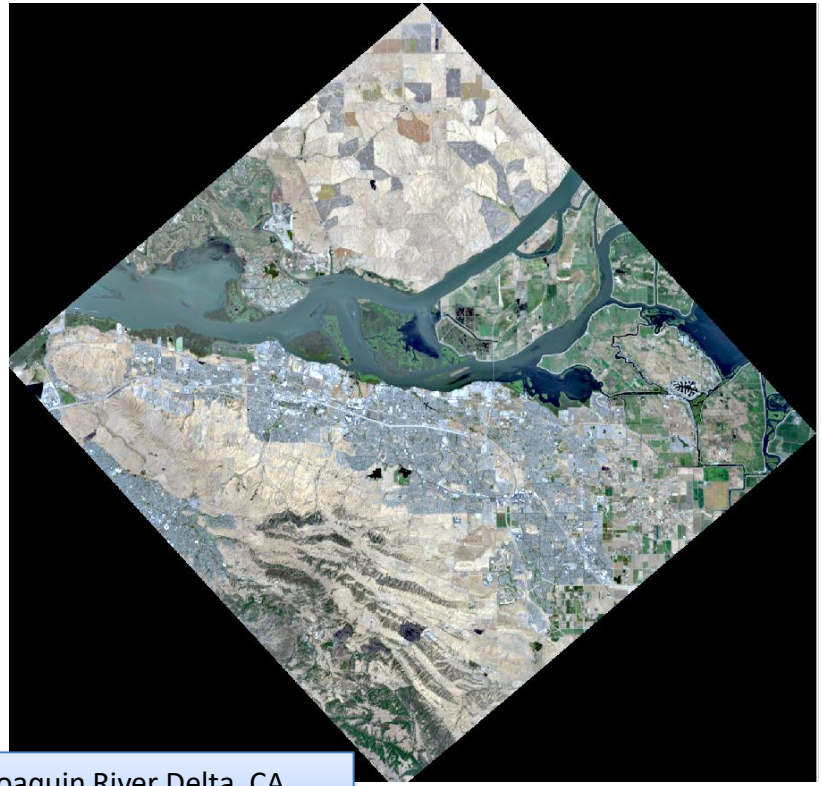


San Joaquin River Delta, CA
August 14, 2019 @ 17:50 GMT

L2A Surface Reflectance

- **Atmospherically-corrected Surface Reflectance product (L2A)**
  - TOA radiance corrected for atmospheric molecular absorption, scattering, and aerosol effects.
    - Radiative transfer look-up-tables generated using MODTRAN.
  - Data corrected using either rugged terrain or flat terrain algorithms.
- **Quality information also includes pixel classification, aerosol optical thickness and water vapor**

Product Coming Soon



San Joaquin River Delta, CA
August 14, 2019 @ 17:50 GMT

Additional Product Options

- **Spectral binning is available for all product levels**
  - Four binning levels - x1 (no binning), x2, x3 and x4 - provide data at 2.55 nm, 5.1 nm, 7.65 nm, and 10.2 nm spectral resolutions, respectively.
    - Currently, < 10 nm spectral resolution data available only to US government agencies and DLR for German government use only.
- **Orthorectified L1C Radiance additional processing options**
  - Map Projection may be UTM or Geographic.
  - Resampling may be Nearest-Neighbor, Bilinear, or Cubic Convolution.
- **Atmospherically-corrected L2A reflectance additional processing options**
  - Terrain Correction either rugged or flat.
  - Ozone Column value.

On-Orbit Performance, Calibration and Validation

On-Orbit Performance

- **On-Orbit performance is continually being evaluated by I2R and DLR**
  - Radiometric, geometric and spatial
- **DESIS is actively acquiring a set of land and water acquisition targets were identified in support of:**
  - Calibration
  - Atmospheric Correction
  - Validation
  - Under flights and Coincident Satellites
- **Detailed description of DESIS performance provided in:**

Alonso, K.; Bachmann, M.; Burch, K.; Carmona, E.; Cerra, D.; de los Reyes, R.; Dietrich, D.; Heiden, U.; Hölderlin, A.; Ickes, J.; Knodt, U.; Krutz, D.; Lester, H.; Müller, R.; Pagnutti, M.; Reinartz, P.; Richter, R.; Ryan, R.; Sebastian, I.; Tegler, M. **Data Products, Quality and Validation of the DLR Earth Sensing Imaging Spectrometer (DESIS).** *Sensors* 2019, *19*, 4471.

Radiometric Accuracy

- **In 2019, vicarious calibration of DESIS was performed to determine the radiometric accuracy of the instrument**
  - Used spectrally smooth scenes, including CEOS pseudo-invariant calibration sites (PICS), and RadCalNet sites.
- **Radiometric performance of DESIS was evaluated using several methods**
  - Comparison to ground truth.
  - Cross-calibration with other satellite sensors.
- **2019 calibration results are provided, although ongoing validation efforts have resulted in updated spectral and radiometric calibration**
  - Expect updated calibration to be released in May 2020.

Ground Truth Comparison

- **DESIS was compared to ground truth values acquired by RadCalNet**
  - CEOS Radiometric Calibration Network currently consists of 4 sites.
  - Provides quality screened 10-nm resolution surface reflectance and scaled TOA reflectance, as well as atmospheric measurements, on a half-hourly basis.
- **RadCalNet TOA reflectance acquired closest in time to DESIS acquisition of a site was converted to TOA Radiance**

$$L_{TOA} = \frac{\rho_{TOA}\, E_0 \cos(SZA)}{\pi\, d^2}$$

Where, L_{TOA} = TOA radiance

ρ_{TOA} = TOA reflectance

E_0 = Thuillier solar irradiance

SZA = Solar zenith angle

d = Earth-Sun distance in astronomical units

RadCalNet Sites Used

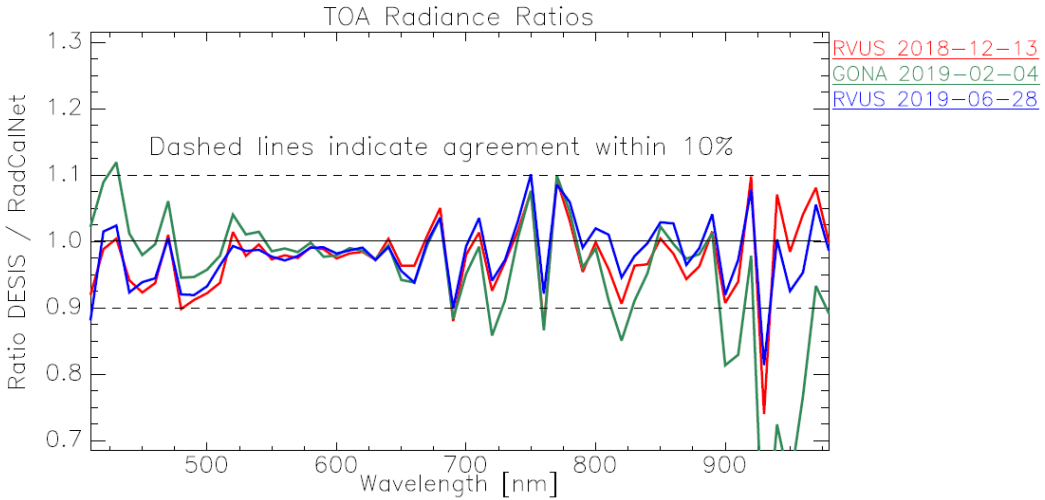
Gobabeb, Namibia
February 4, 2019 @ 8:45 GMT

Railroad Valley, NV
June 28, 2019 @ 18:53 GMT

= approximate area used in analysis

Ground Truth Comparison Results

- **DESIS data was compared to three RadCalNet data sets**
  - Railroad Valley 12/13/18 and 6/28/19
  - Gobabeb, Namibia 2/4/19
- **DESIS agrees with RadCalNet within 10%, except for atmospheric absorption features**



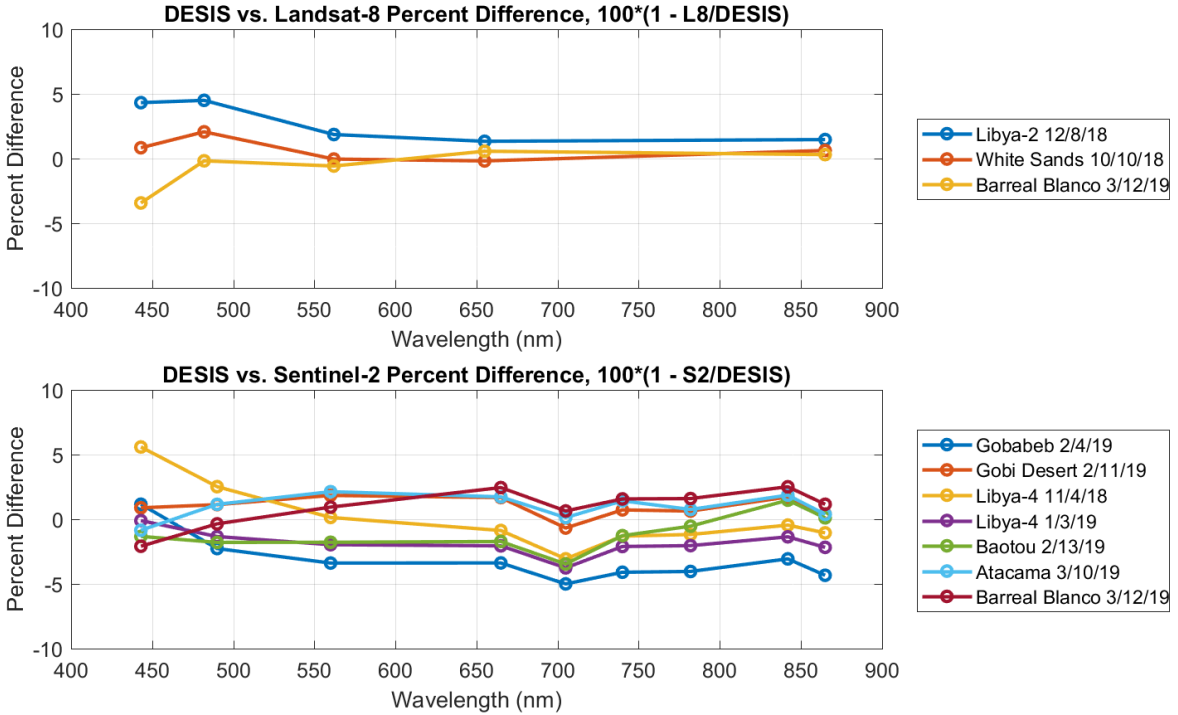
Cross-Calibration

- **DESIS compared to other well-calibrated sensors for independent verification of radiometric accuracy**
  - Landsat-8 OLI and Sentinel-2 MSI (A & B).
- **Near coincident data sets, acquired within one hour and with low view zenith angles over high reflectance pseudo-invariant sites were used**
  - 3 Landsat-8 acquisitions and 7 Sentinel-2 acquisitions.
- **DESIS L1B 2.55 nm radiance used for comparison**
  - Data converted to TOA reflectance

$$\rho_{TOA} = \frac{\pi \, L_{TOA} \, d^2}{E_0 \cos(SZA)}$$

- **DESIS hyperspectral data band integrated to match multispectral sensor resolution**

Cross-Calibration Results



Cross-Calibration Summary

- **For similar Landsat-8 and Sentinel-2 bands, percent differences from DESIS for both sensors were combined**
- **The mean differences between DESIS and the comparison sensors were all < 1%**
  - Very little bias in the radiometric accuracy with largest variation in the lower wavelengths.

Statistic	Coastal Aerosol (~443 nm)	Blue (~482 nm)	Green (~562 nm)	Red (~655 nm)	NIR (~865 nm)
Mean Percent Difference	0.50	0.54	-0.08	-0.04	-0.31
Standard Deviation	2.77	2.13	1.86	1.92	1.76

Geometric Accuracy

- **177 scenes used to assess geolocational accuracy**
  - ~ 210 GCP points per scene were used to correct imagery.
  - ~ 968 control points per scene were used to assess accuracy.
- **With image matching technique, linear RMSE was less than 1 pixel**
  - 21.0 ± 5.9 m Easting RMSE
  - 21.4 ± 6.0 m Northing RMSE
- **Without image matching, errors were found to be 298 m across track and 496 m along track RMSE**

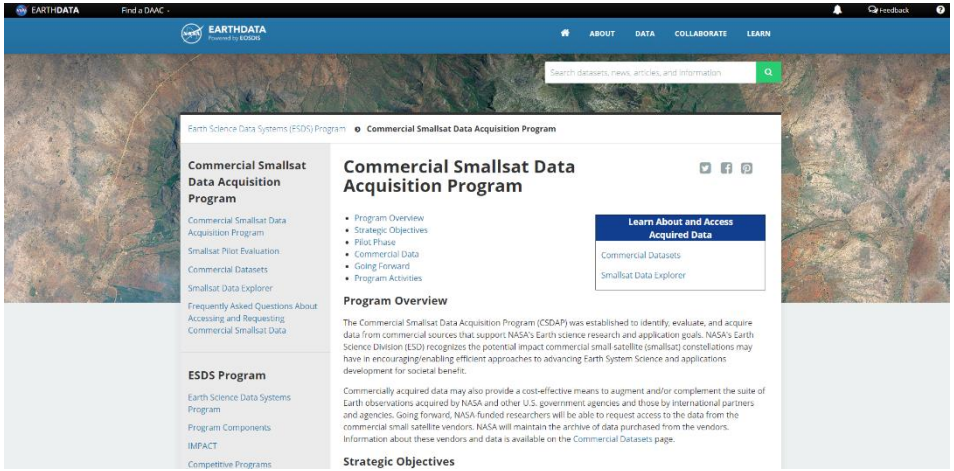
Spatial Resolution

- **Spatial resolution of the DESIS L1B 10.2 nm spectrally binned data was estimated**
  - Modulation Transfer Function (MTF)
  - Edge Slope (ES)
- **Because of ISS orbit, cardinal oriented targets cannot be used to estimate along-track and cross-track parameters**
  - A set of large agricultural fields was identified that create near ideal cross-track edge responses.
  - DESIS has been tasked to acquire additional imagery over this and other similar areas.
- **Initial results show the cross track MTF@Nyquist exceeds 0.3**
  - Future work will evaluate along-track spatial resolution, which will likely be slightly lower than the cross-track direction.

DESIS Hyperspectral Imagery Catalog

Data Access

- Catalog can be browsed here: Teledyne.tcloudhost.com
- Catalog data freely available to NASA and US federal Research Scientists via NASA contract. Yvonne Ivey is the POC for catalog access
- Commercial applications are not covered by the NASA agreement. Imagery must be purchased separately
- DESIS will eventually be available here: https://earthdata.nasa.gov/esds/small-satellite-data-buy-program



Fine print: 2.55nm resolution only available to US Gov and DLR.

DESIS APPLICATIONS

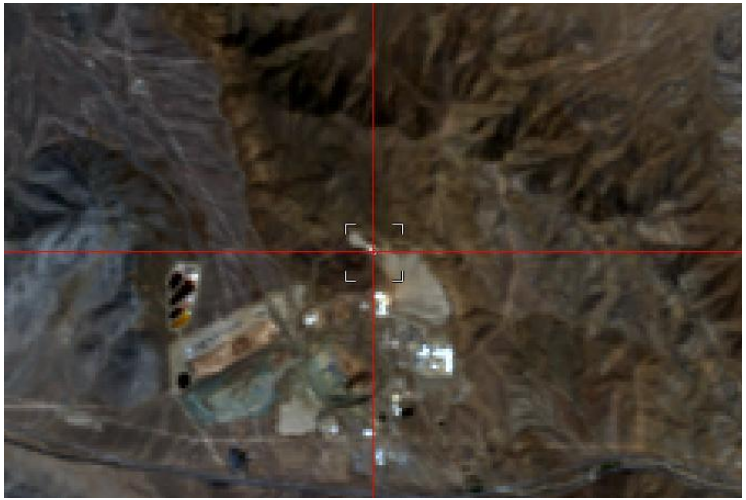
Opportunities to Work With Other Instruments

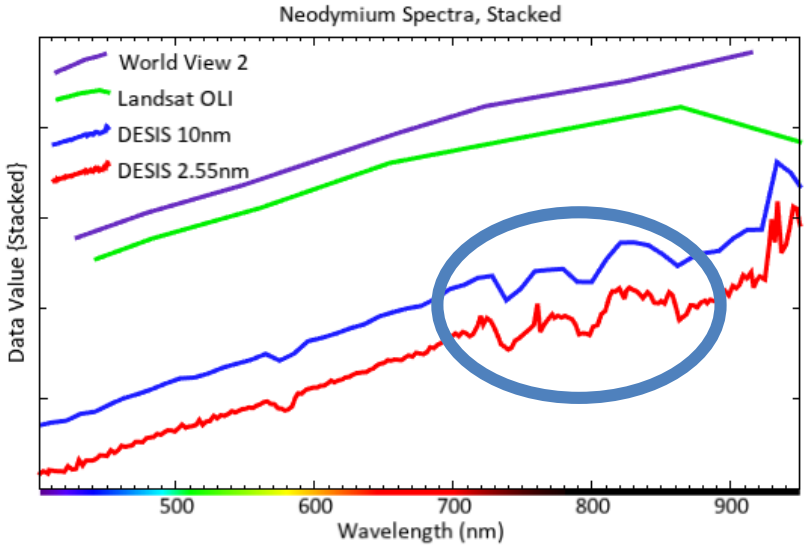
- With the calibration attention to detail and tools like Python, ENVI and Erdas you can compare DESIS data other datasets (Landsat/Sentinel-2).
- By resampling DESIS to multispectral wavelength you can determine if certain spectral features are observable with other MSI instruments, or what bands are most important.
- Since DESIS has VNIR bands, it can be stacked with other sensors with SWIR channels to enhance analytic degrees of freedom.
- DESIS can be used to simulate sensors, show hyperspectral applicability and test what a high signal to noise satellite can detect.

Example: Rare Earth Elements

- Using ENVI's resampling tools we can see that the absorption features that define REEs disappear with Landsat and WV2 band passes
- Gregg Swayze from USGS SpecLab:

  "So this may be the first demonstration of REE detection from space but may also have high enough resolution and SNR to allow differentiation of individual REE minerals."
- Because of DESIS' image quality, this application is a reality.

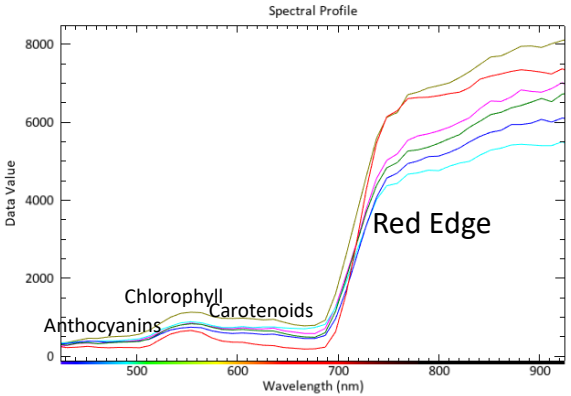




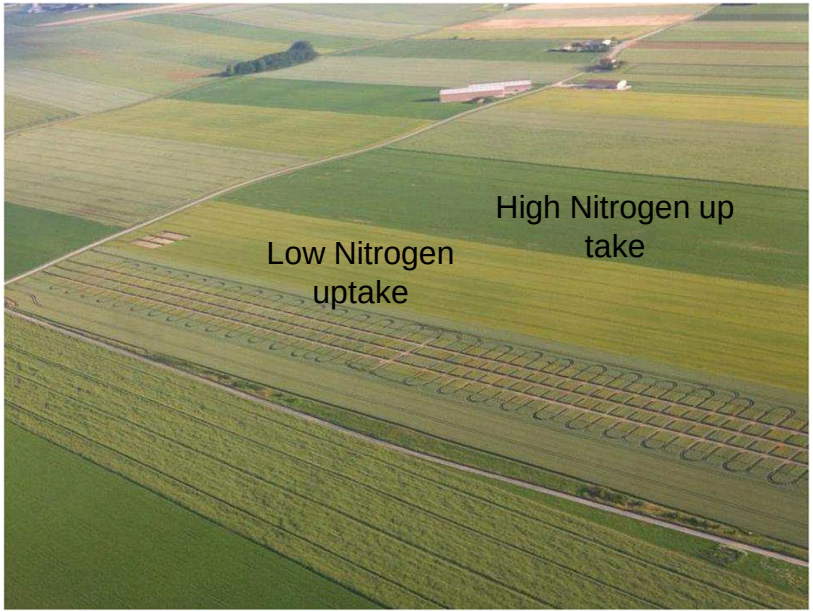
Example: Vegetation and Food Security

- 30m resolution effective for regional area analysis and trend analysis.
- Hyperspectral data sensitive to vegetation pigments that can indicate stress.
- Stress over time can create food insecurity and lead to geopolitical instability. W COVID 19, understanding crop health in key zones more important.
- Pigments can be used to observe specific kinds of nutrient stress, stacked with Landsat or sentinel-2 SWIR bands can help understand water stress and nutrient stress.

DESIS 2.55nm Res Spectral



Different Wheat Phenotype Nitrogen absorption



David Gouache, SPIE Newsroom 2016

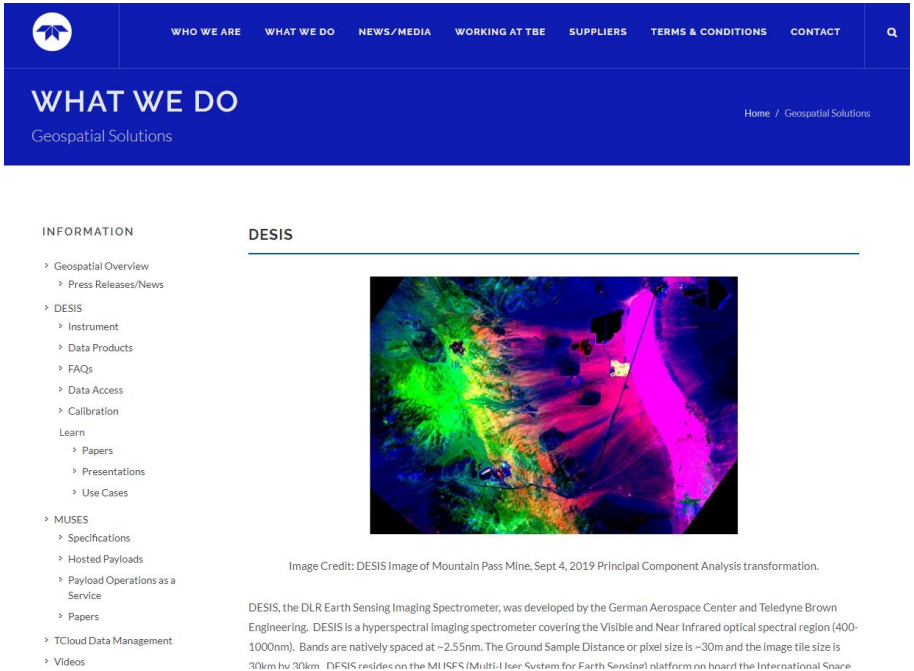
ROSES

- Research Opportunities in Space and Earth Sciences 2020 (ROSES-2020)
  - Solicitation: NNH20ZDA001N
- Specific call for ISS instrumentation
- Because of DESIS excellent calibration can be used to augment other ROSES responses with these unique data.
- DESIS can be used with other NASA RFQs, please contact Amanda O'Connor for questions on DESIS applications and/or capabilities.

RESOURCES

TBE Website

- **TBE.com/Geospatial**
  - Detailed instrument specifications
  - White papers
  - Use cases
  - Goal to have a forum up soon
  - @TeledyneBrown on Twitter
- **Teledyne.tcloudhost.com**
  - Share with colleagues
  - Contact Yvonne or Amanda for access



Questions?
Answers
Next Steps

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