CUAD: Constellation for Upper Atmosphere Dynamics

Larry Gordley, B. Thomas Marshall, David C. Fritts
Global Atmospheric Technologies and Sciences (GATS)
John Fisher
Brandywine Photonics, Exton, PA
Marian Klein
Boulder Environmental Sciences and Technology (BEST)

GSFC, Greenbelt, MD
December 1, 2017

GATS Founded 1986

Upper atmosphere dynamics research
- Planetary, GW, Tides
- Turbulence

Upper Atmosphere Sensors
- Conceptual design
- Performance analysis
- Data inversion
- Instrument operations
- On-board processing

Radar, LIDAR, Radiometers
- Ground based
- In-orbit

Occultation
Limb emission
Nadir emission

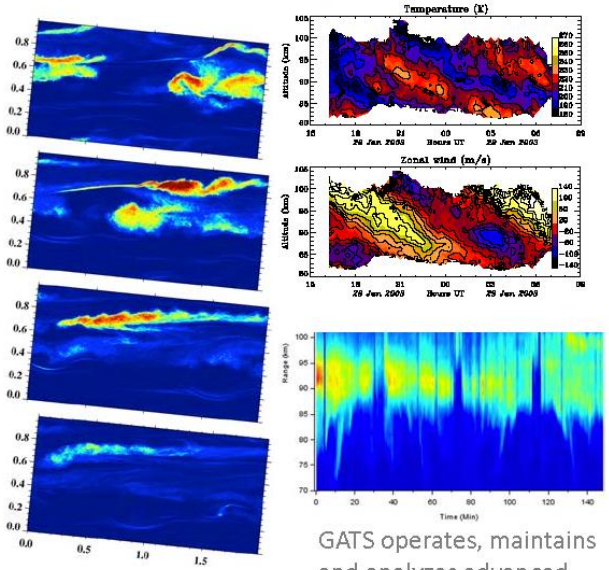
Instrument operations
Data Processing systems
IR radiative transfer modeling
GHG sensor design
Gas filtering and correlation expertise

GATS Global Atmospheric Technologies and Sciences

Satellite Remote Sensing

GATS has provided instrument design, flight operations, science analysis, retrieval algorithms, data management and ground systems for NASA atmospheric science missions since 1986.

Measurement and Modeling of the Earth's Atmosphere

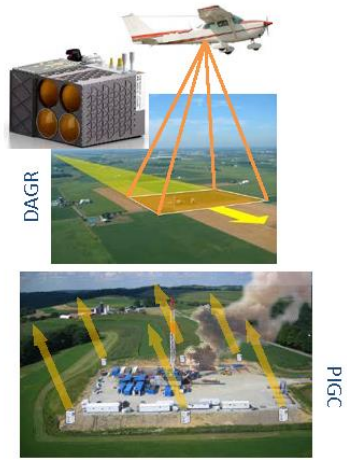


Our supercomputer simulations of turbulence help improve weather forecasts and predict energy consumption.

GATS operates, maintains and analyzes advanced laser systems and radar stations that measure the processes influencing our weather and upper atmospheric dynamics.

GATS has a portfolio of novel sensor concepts, for space (DWTS, HATS, TStar, and GLO), with patented processing techniques. Ground and air systems include various implementations of DAGR and PIGC. See our website: www.gats-inc.com

Environmental Monitoring Solutions



DAGR and *PIGC* are breakthrough commercial solutions for monitoring greenhouse gases and pollutants.

SpectralCalc.com
High-resolution spectral modeling

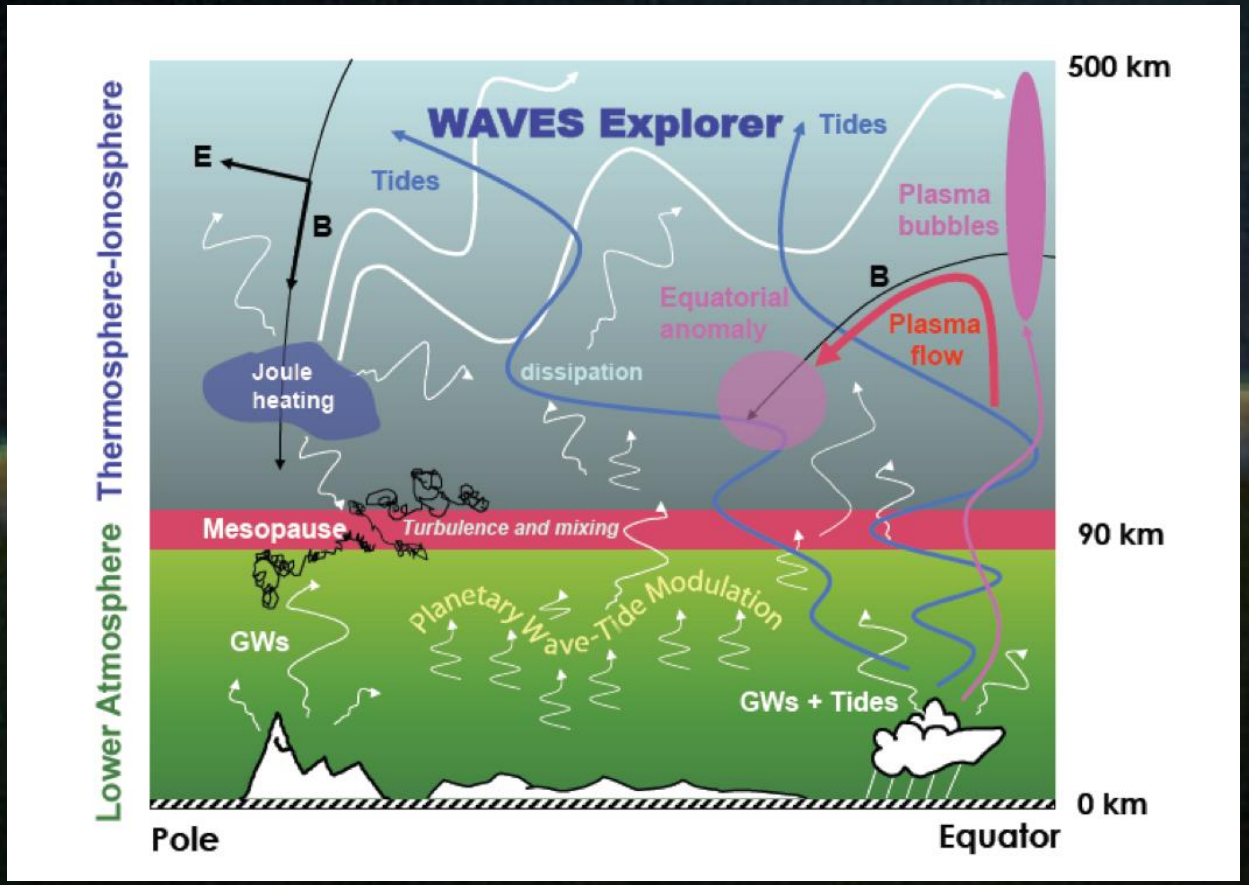
Our web-based modeling tools are used by researchers and teachers around the world.

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

GSFC, Greenbelt, MD
December 1, 2017

Dynamic coupling of lower to upper atmosphere is huge relatively unobserved

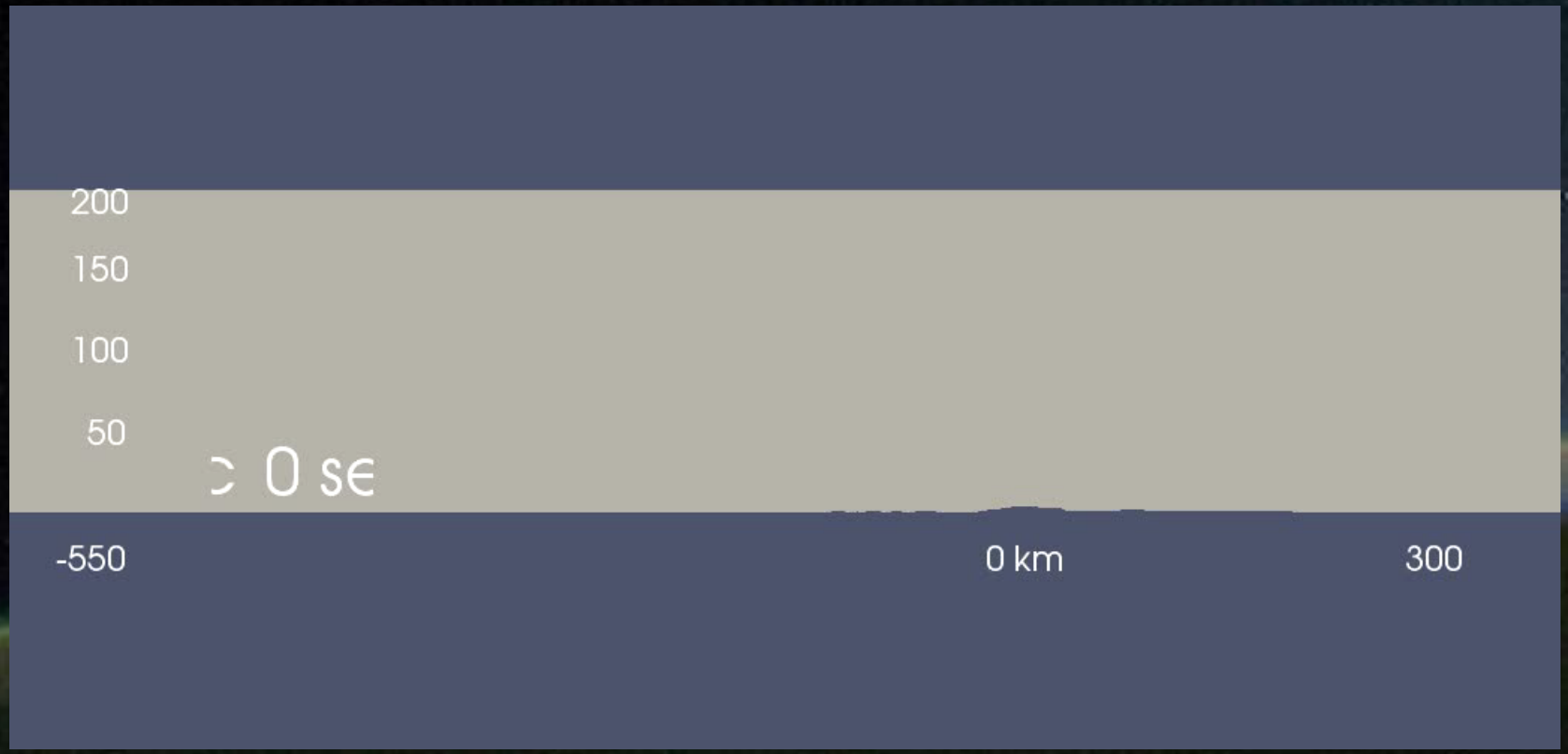
- Lower atmosphere dynamics impacts thin upper atmosphere
- Imprints weather signature into the upper atmosphere.
- Only now learning how to read the coupling language
- But, it is largely unobserved
- *THAT VOID CAN NOW BE ELIMINATED*



Gravity wave effects generated by surface winds in the Andes

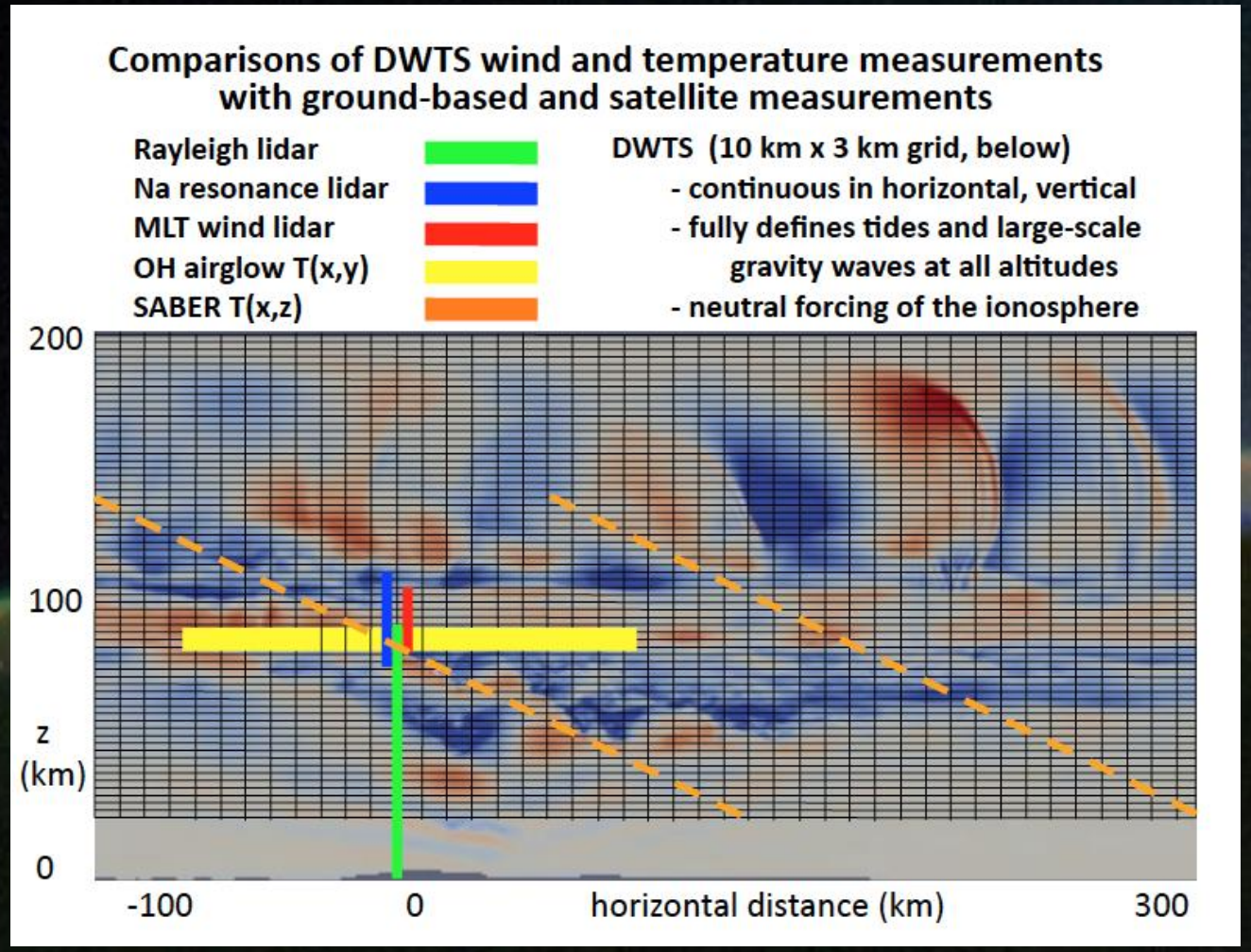
Zonal wind field near 50° south from gravity waves generated by winds over Argentine Mountains
Surface winds ramp up over 1 hour, kept constant for the second hour.

Courtesy
Tom Lund of
NWRA



Maximum upper atmosphere winds about 100 m/s

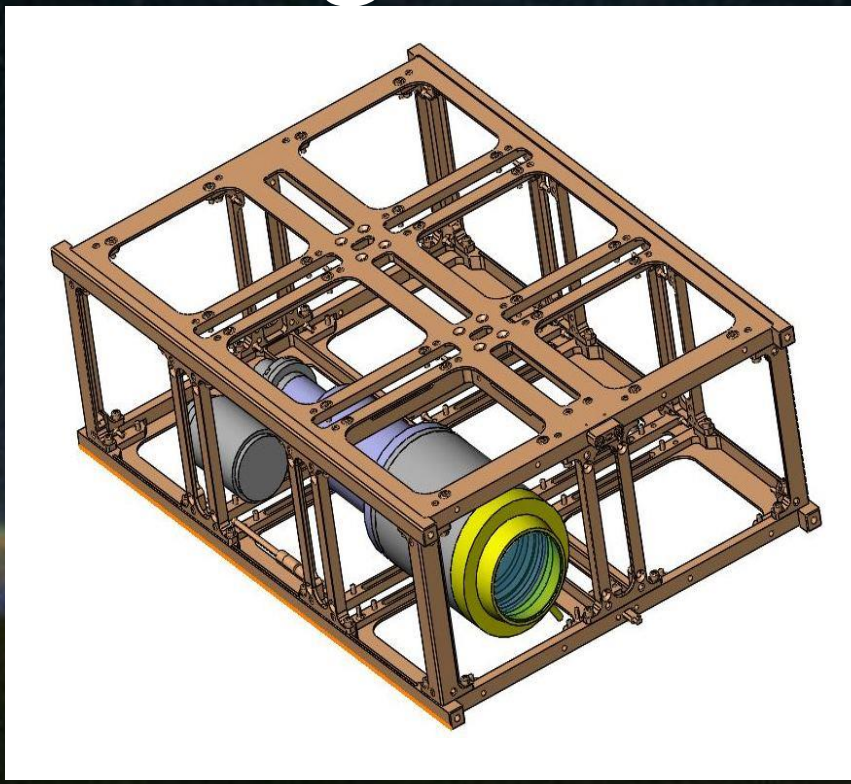
Technique Comparisons



A Path to Wind and Temperature from Cloud-Top to over 150 km, day *and* night 6Uu

- Now Possible with four multi-image static sensors & DSGF (Doppler Scanning Gas Filters)
  - HATS --- High Altitude Thermal Sounder
    - Nadir CO_2 thermal emission multi-imager (~ 7)
    - Doppler Scanning with Gas Filters (DSGF)
    - Limb look for gas cell and absolute calibration
  - DWTS --- Doppler Wind and Temperature Sounder (limb)
    - Milti-imager (3) of limb emission
    - Wind and Temperature (no radiance calibration required)
  - LCER --- Broadband CO_2 limb emission imager
    - Temperature profiles possible without absolute calibration
    - Also provides CO_2 fields
  - TStar --- Limb star tracker
    - Refraction based temperature profiles
    - Calibration anchor of entire CUAD system

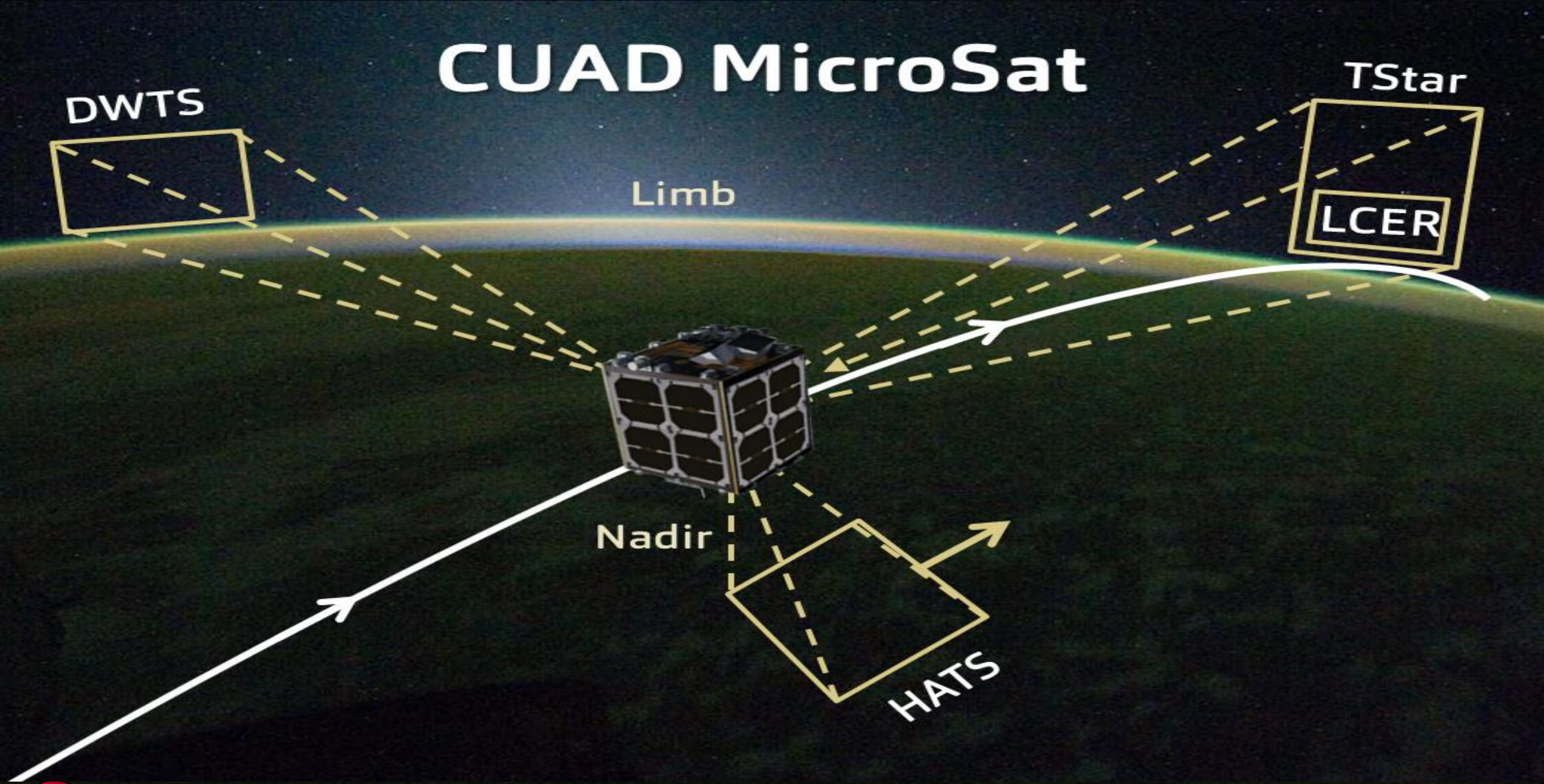
Elegant Simplicity



HATS High Altitude Temperature Sounder
DWTS Doppler Wind and Temperature Sunder
LCER Limb CO2 Emission Radiometer
TStar Temperature from Star imaging

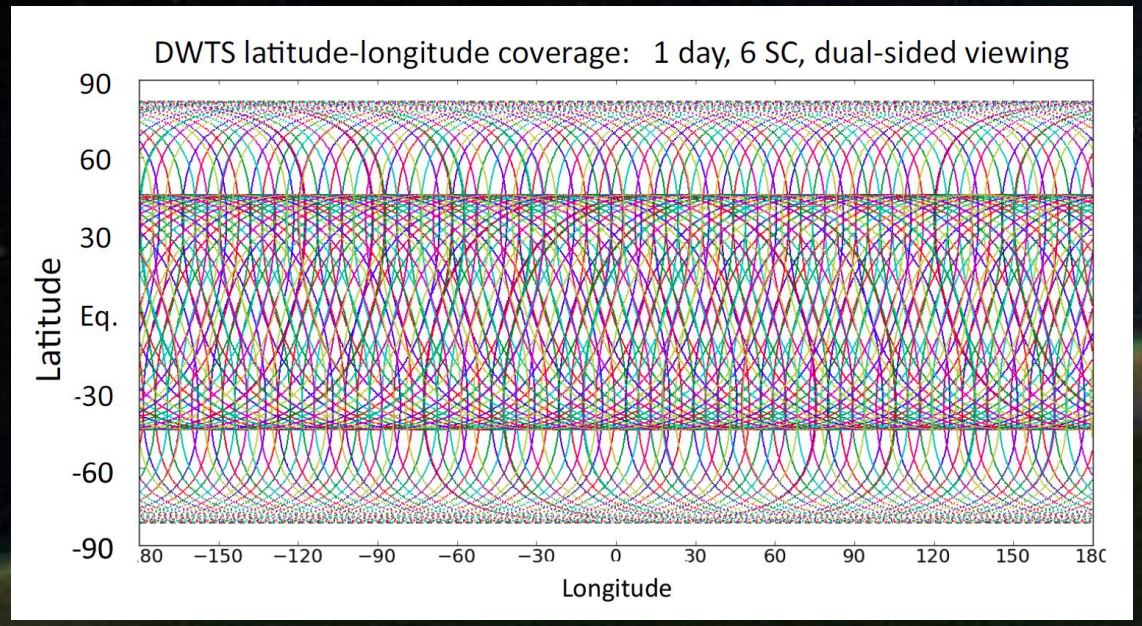
GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

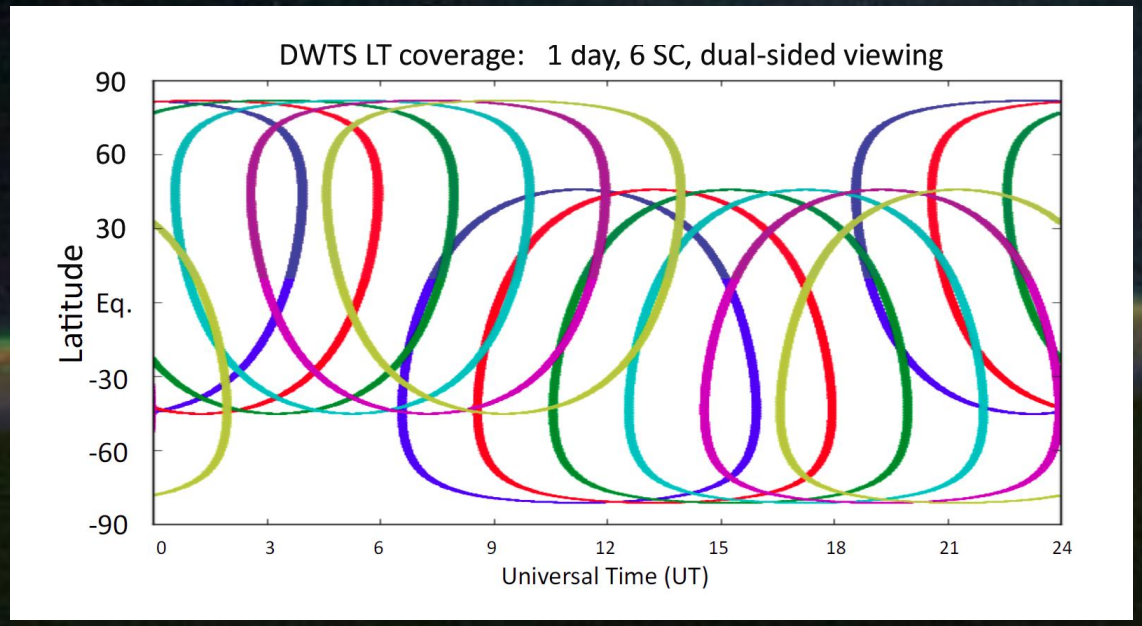
GSFC, Greenbelt, MD
December 1, 2017


CUAD MicroSat
DWTS
TStar
LCER
Limb
Nadir
HATS

Global coverage

Dense coverage allows colocation
for calibration objectives





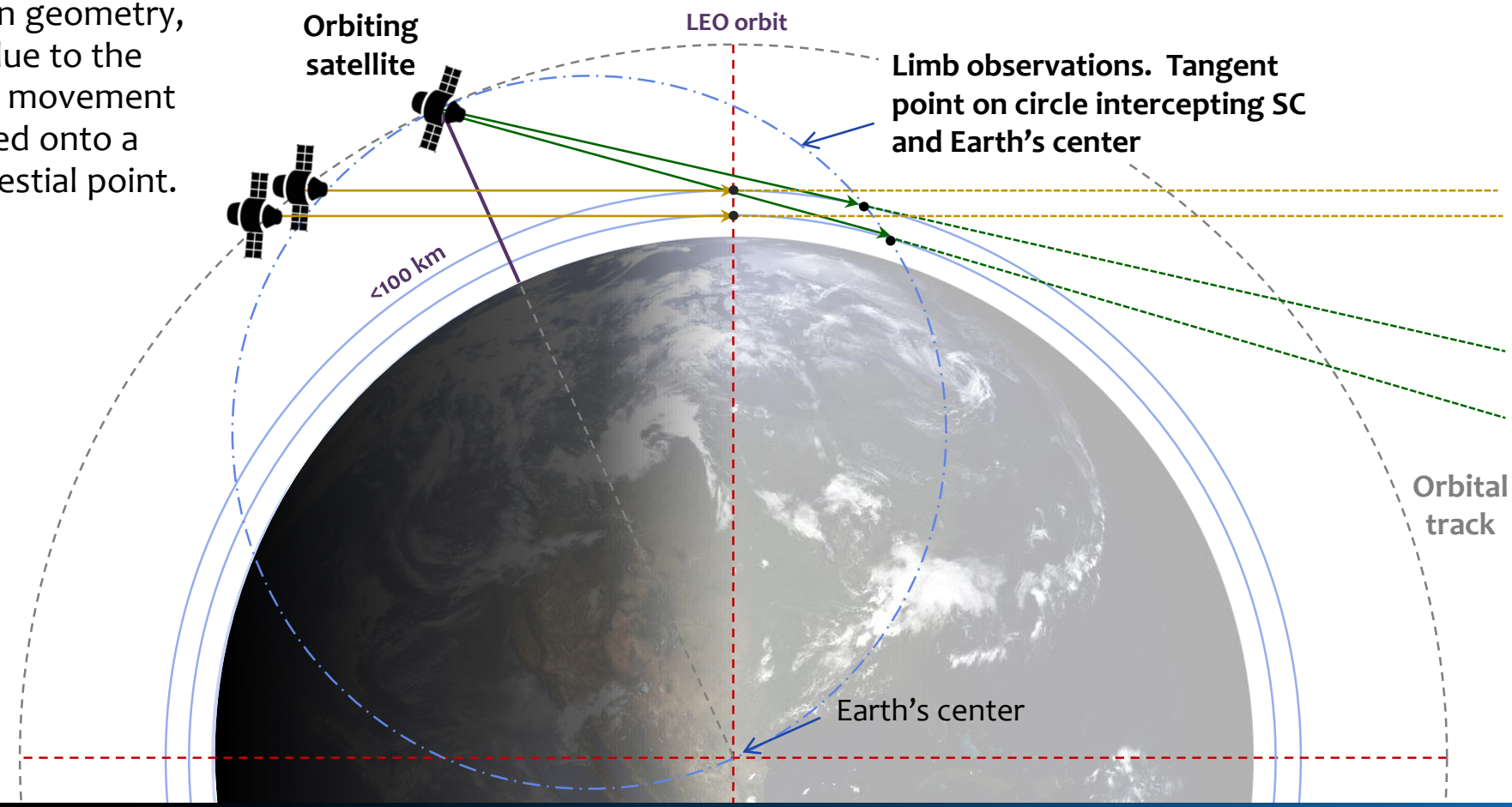
DWTS daily lat-lon & LT sampling on 6 COSMIC-2 SC at 800 km and 72° inclination.

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

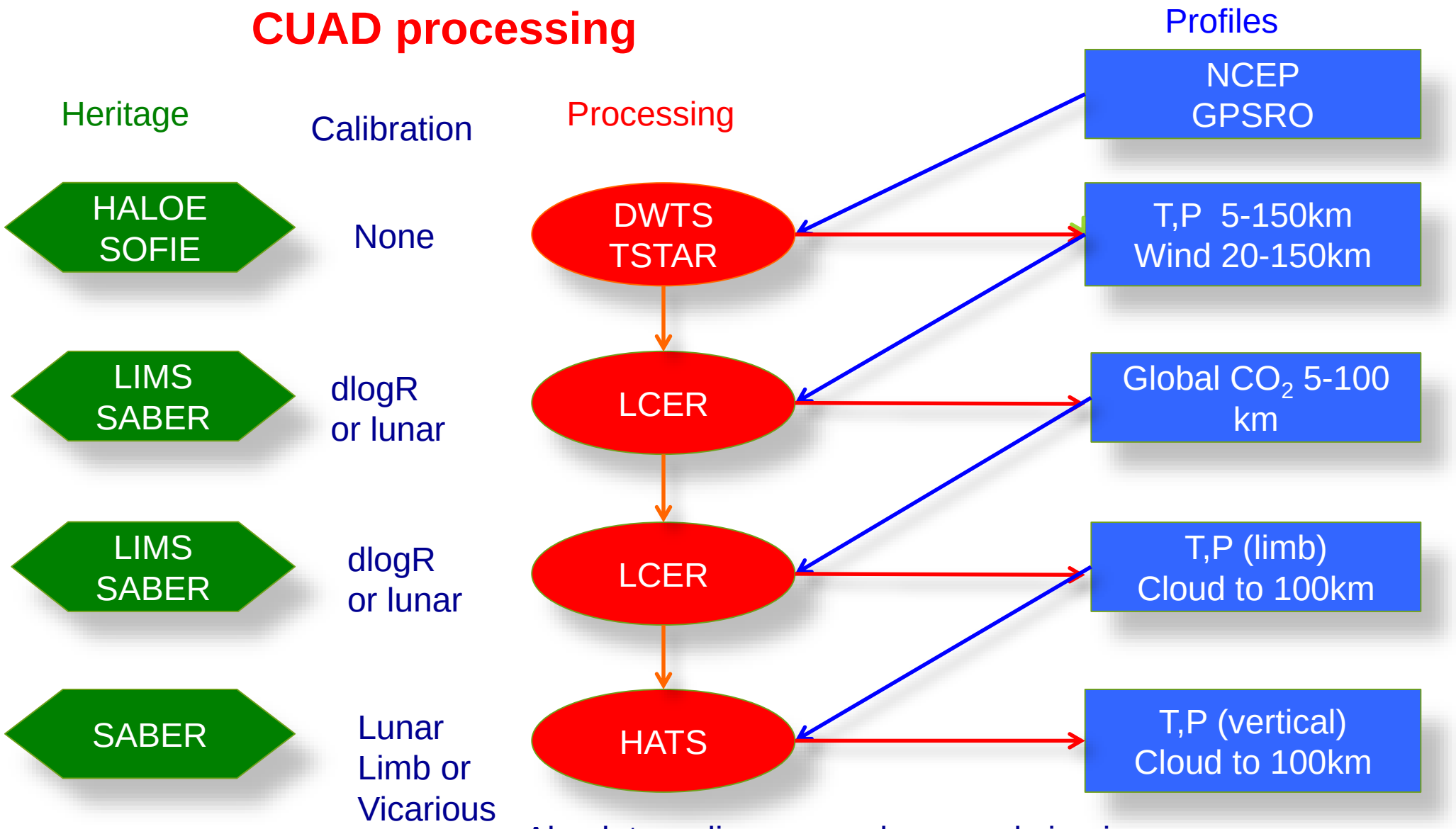
GSFC, Greenbelt, MD
December 1, 2017

ADCS and GPS provides accurate measurement location, enabling critical synergy of sensors

Occultation geometry, scanning due to the spacecraft movement while locked onto a distant celestial point.



CUAD processing



Other calibration

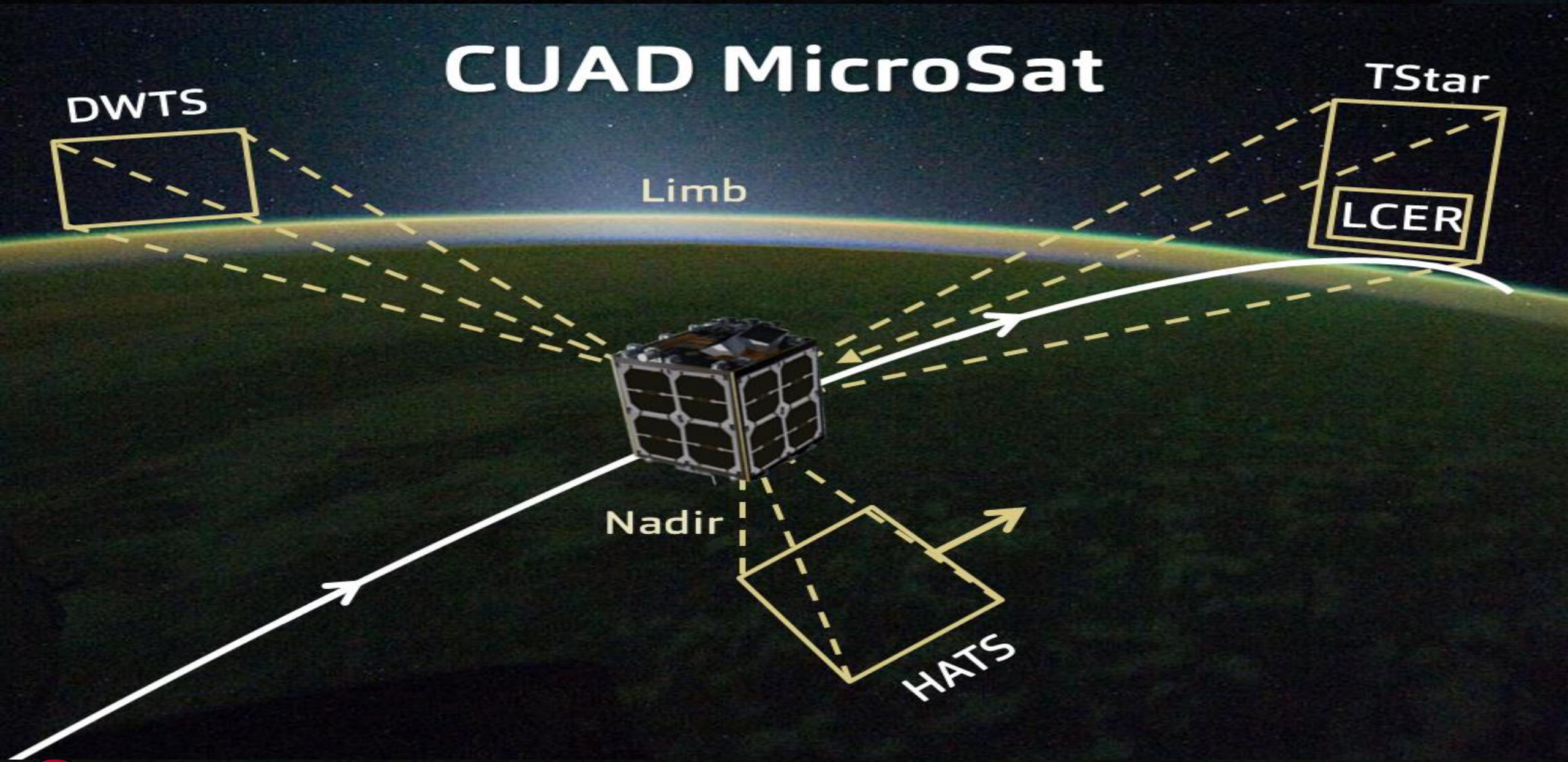
Absolute radiance ---- lunar and vicarious
Gas cell ---- limb Doppler
Stray light ---- lunar, limb, solar
scan

GATS Global Atmospheric Technologies and Sciences

GPI Gas Plume Imaging Ground·Air·Space

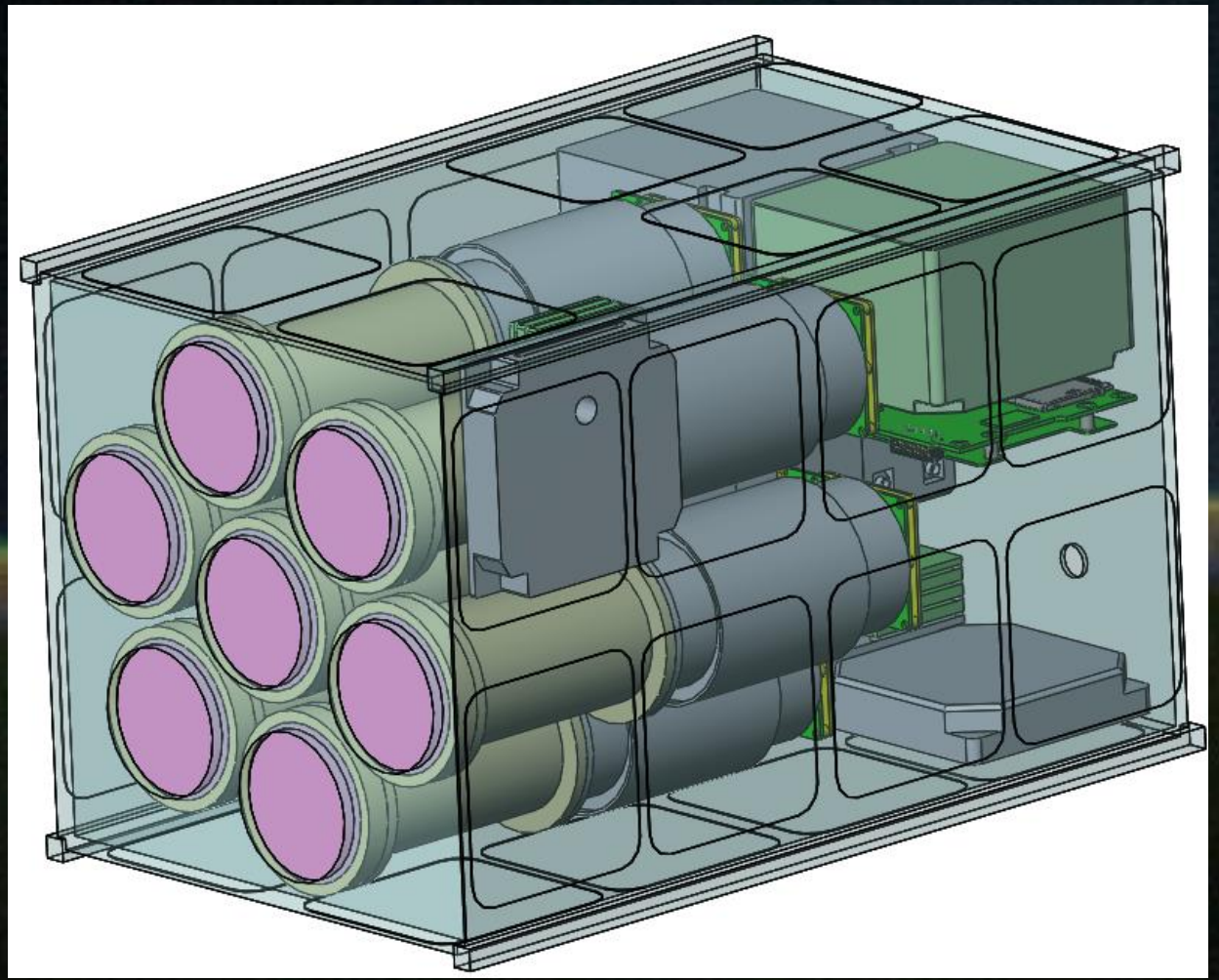
BRANDYWINE PHOTONICS

GSFC, Greenbelt, MD
December 1, 2017


CUAD MicroSat
DWTS
TStar
Limb
LCER
Nadir
HATS

HATS Instrument Concept

16 U example (12U may be possible)
7 Nadir viewing channels/sensors
20 degree FOV
Primary challenge is cooling

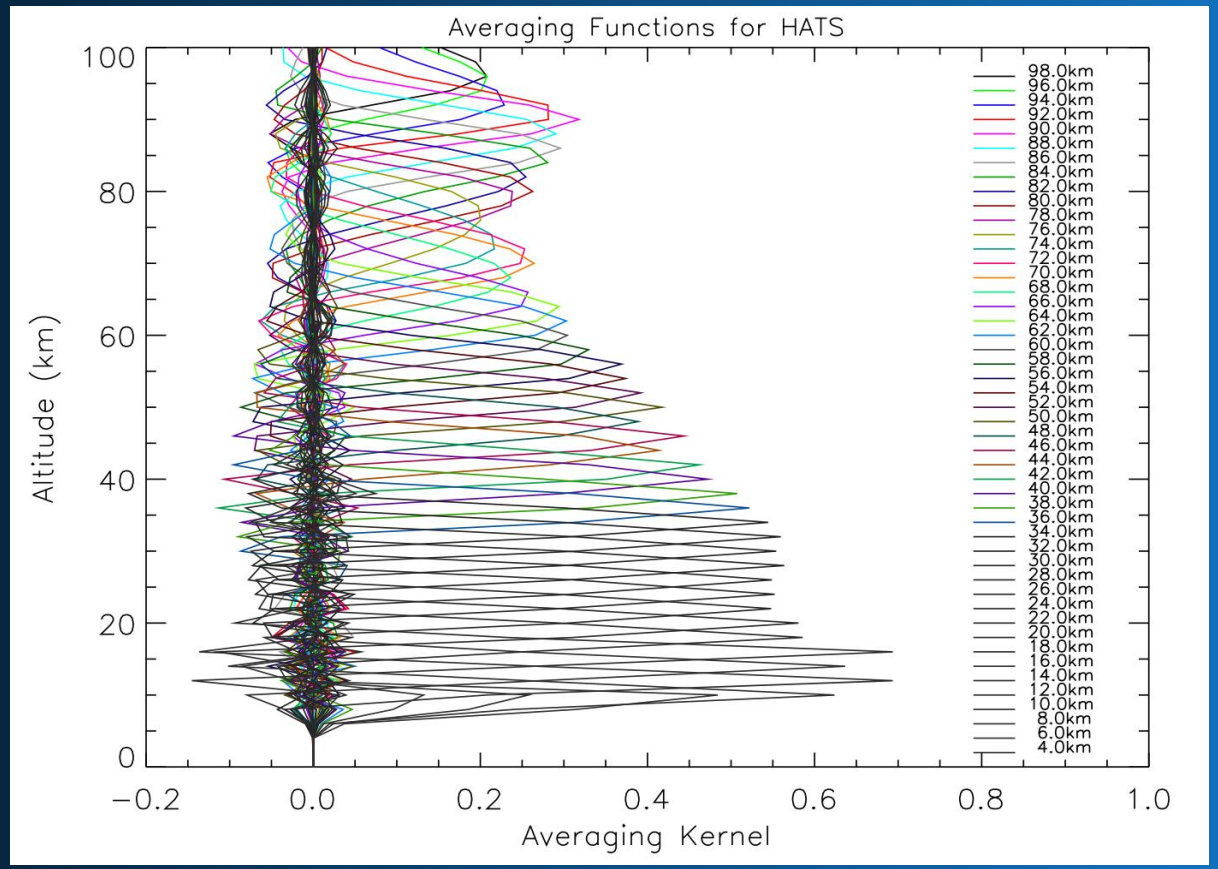


GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS BOULDER ENVIRONMENTAL SCIENCES & TECHNOLOGY

HATS™ – High Altitude Thermal Sounder

- Averaging kernels resulting from 7 selected bands, each observed by a separate imager.
- Derived from principal component analysis of the 7 modulation functions produced during Doppler scans
- Potential 10-20 km horizontal resolution

White Paper available



Concept first suggested by:

P. D. Curtis, J. T. Houghton, G. D. Peskett and C. D. Rodgers

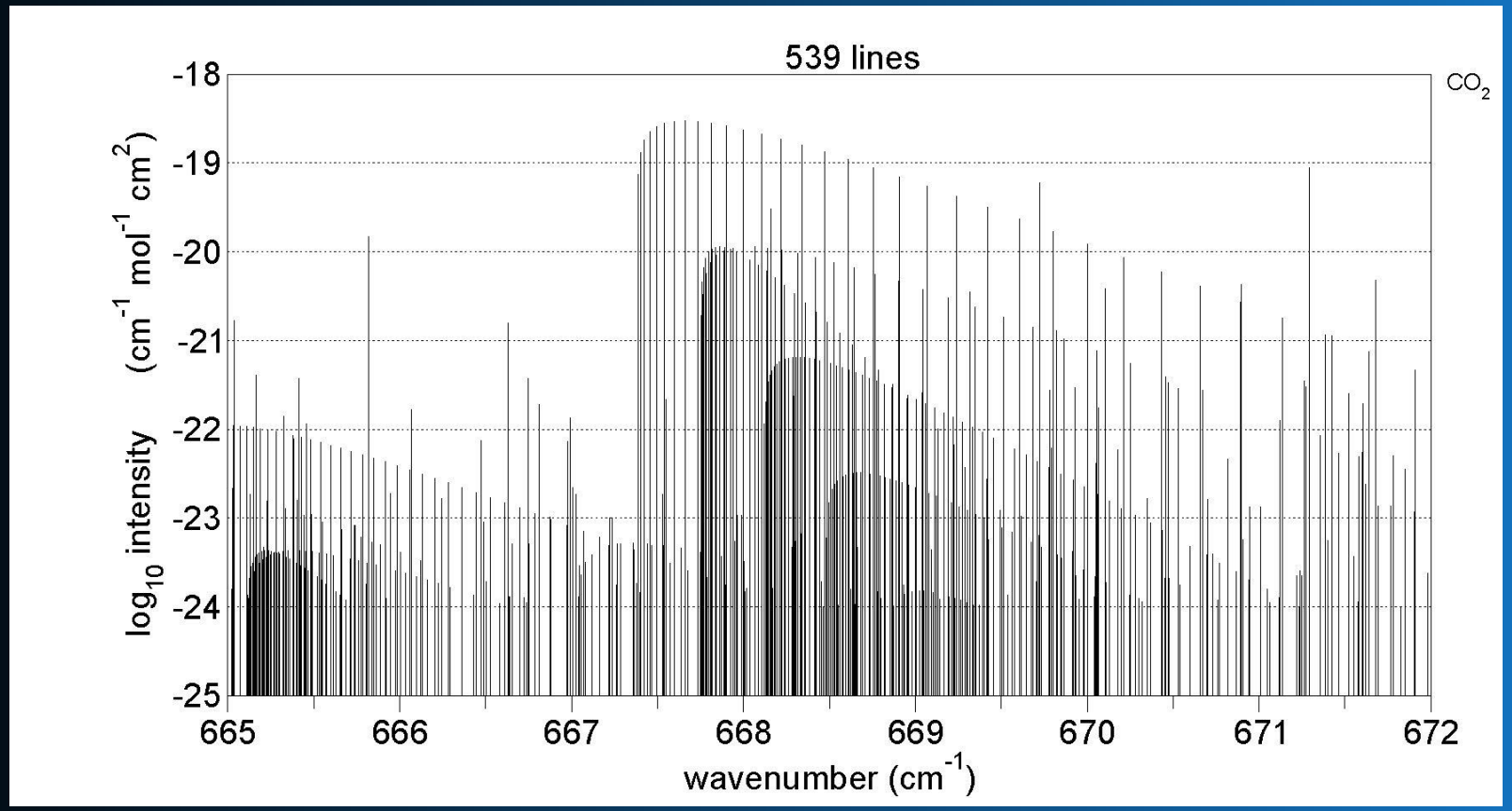
Proc. R. Soc. Lond. A 1974 **337**, 135-150
doi: 10.1098/rspa.1974.0042

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

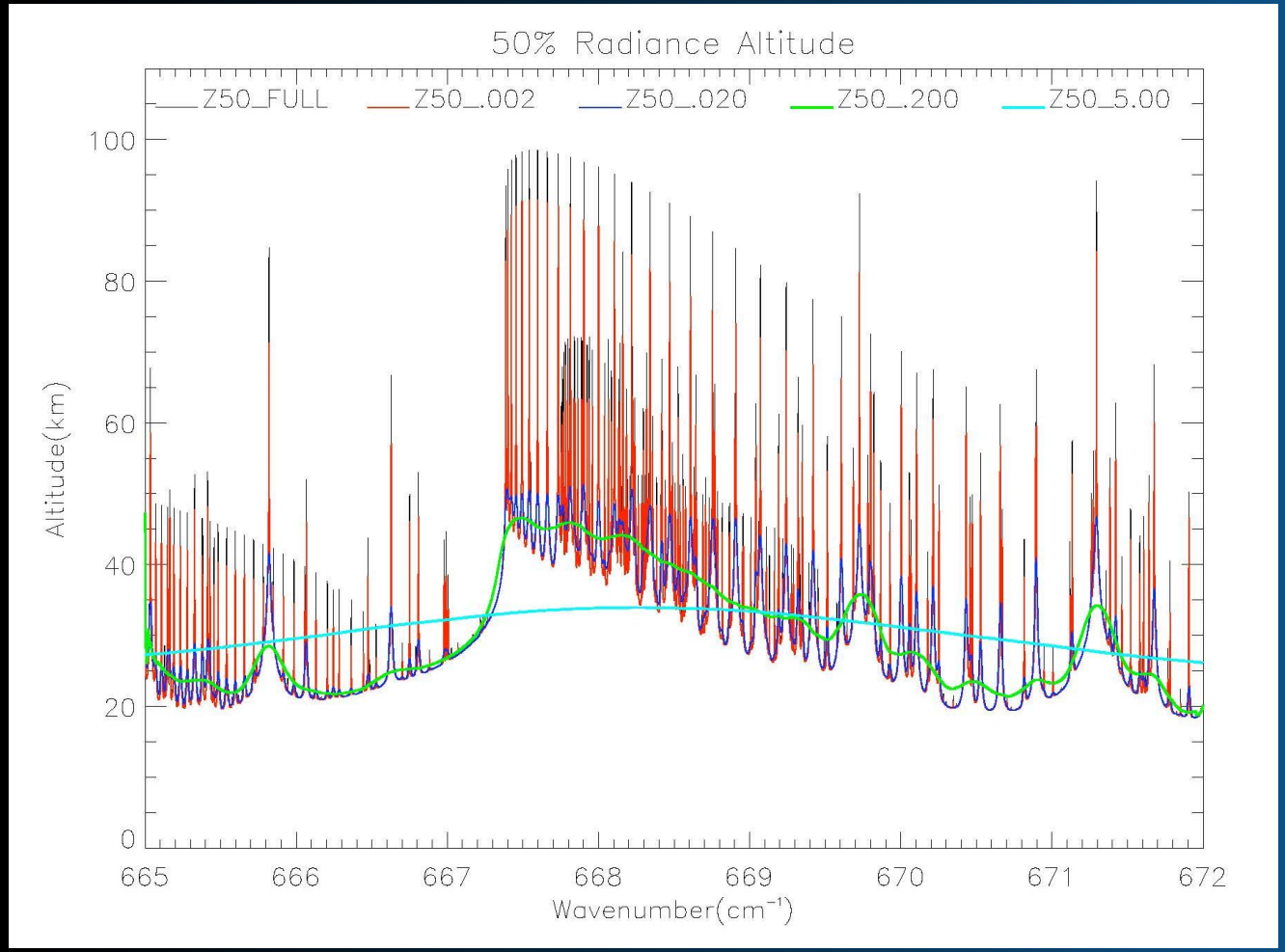
GSFC, Greenbelt, MD
December 1, 2017

Look down at CO_2 emission

- CO_2 near 15 μm
- Can we thermally sound?
- Yes, but it *requires very high resolution*
- Doppler scanning (DSGF) solves that problem



Mean Altitude of Emission for various resolutions



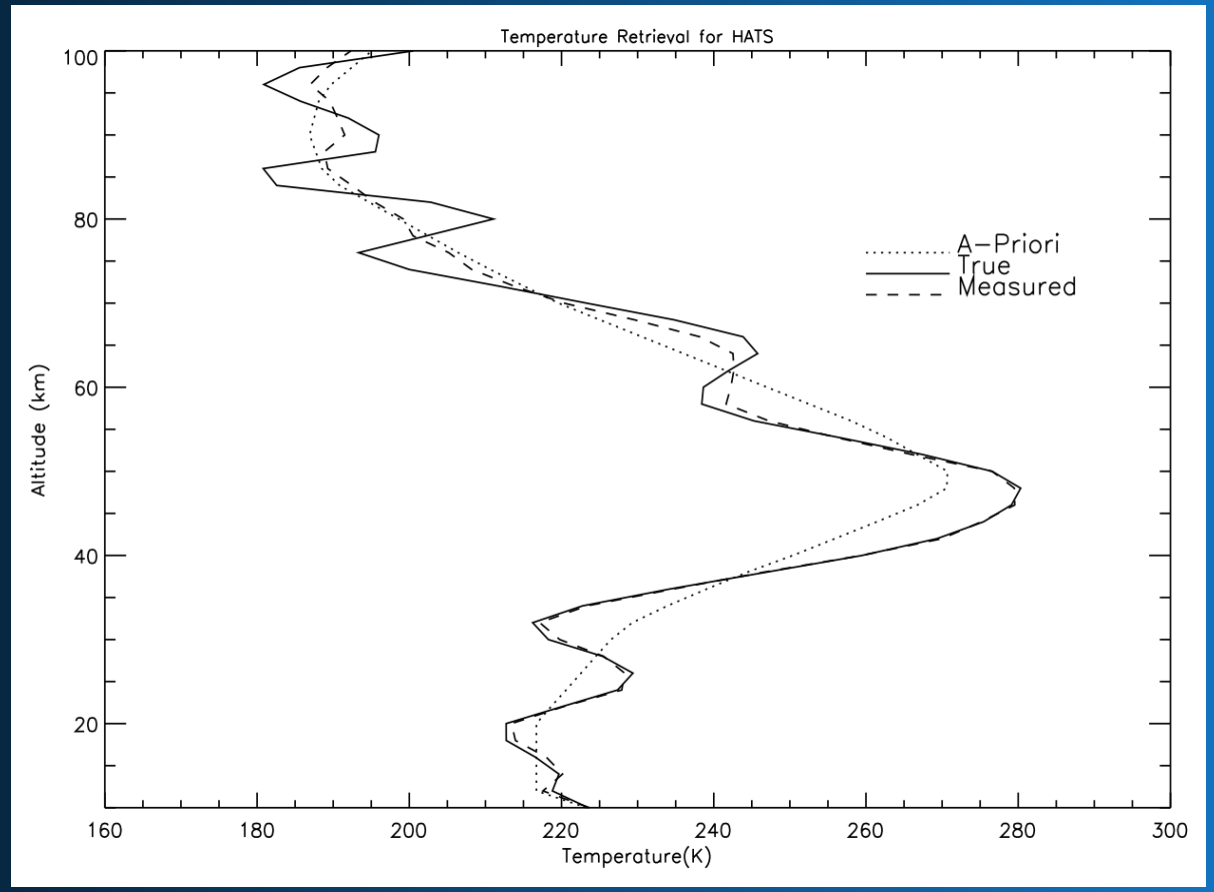
GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

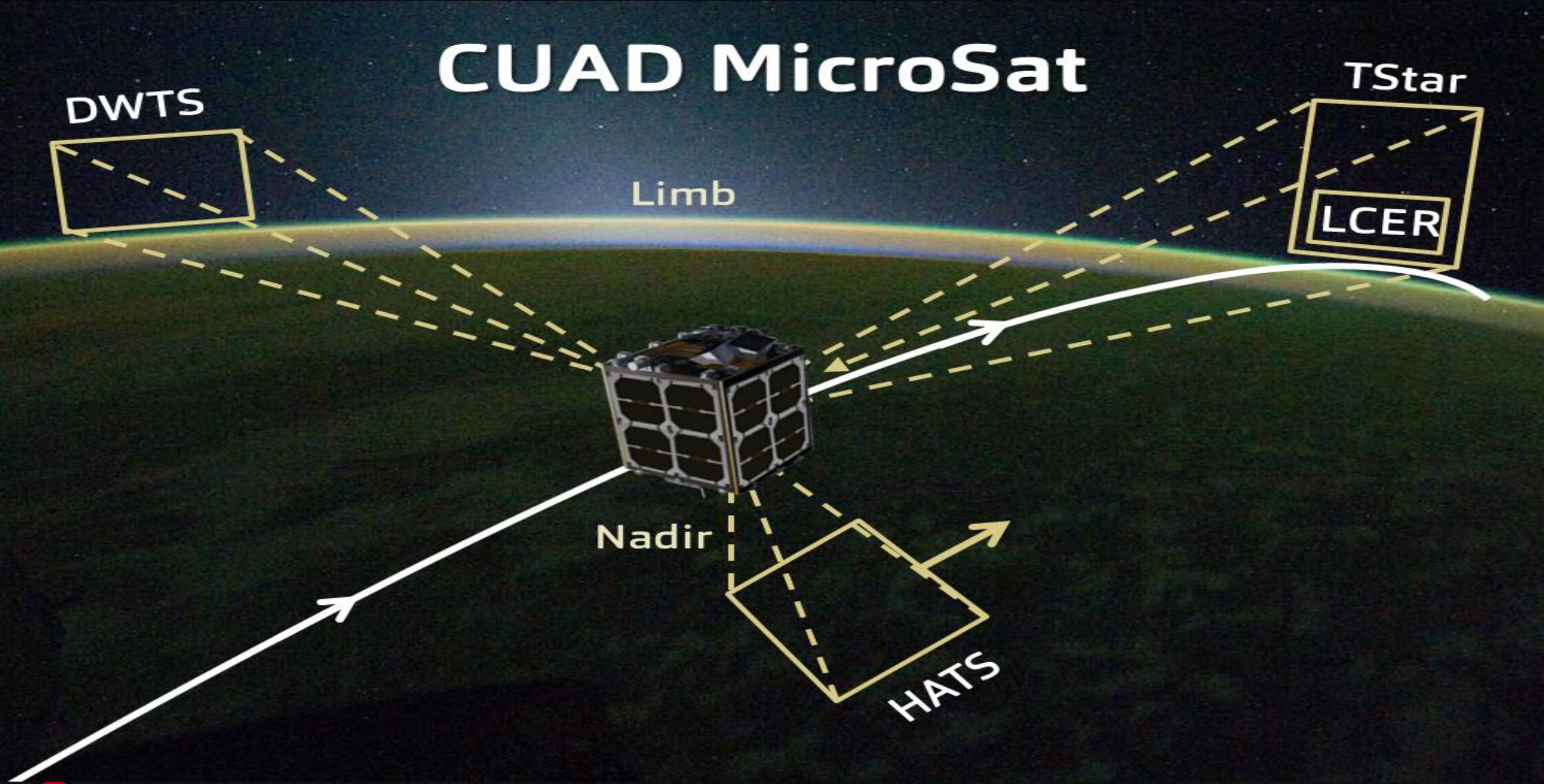
GSFC, Greenbelt, MD
December 1, 2017

HATS™ temperature retrieval

- The dotted is the a priori profile (the guess)
- The solid is the truth
- The dashed is the retrieved
- The optimal estimation technique uses the measurements to estimate the "differences" between the a priori guess and the truth

White paper on HATS is available on request.

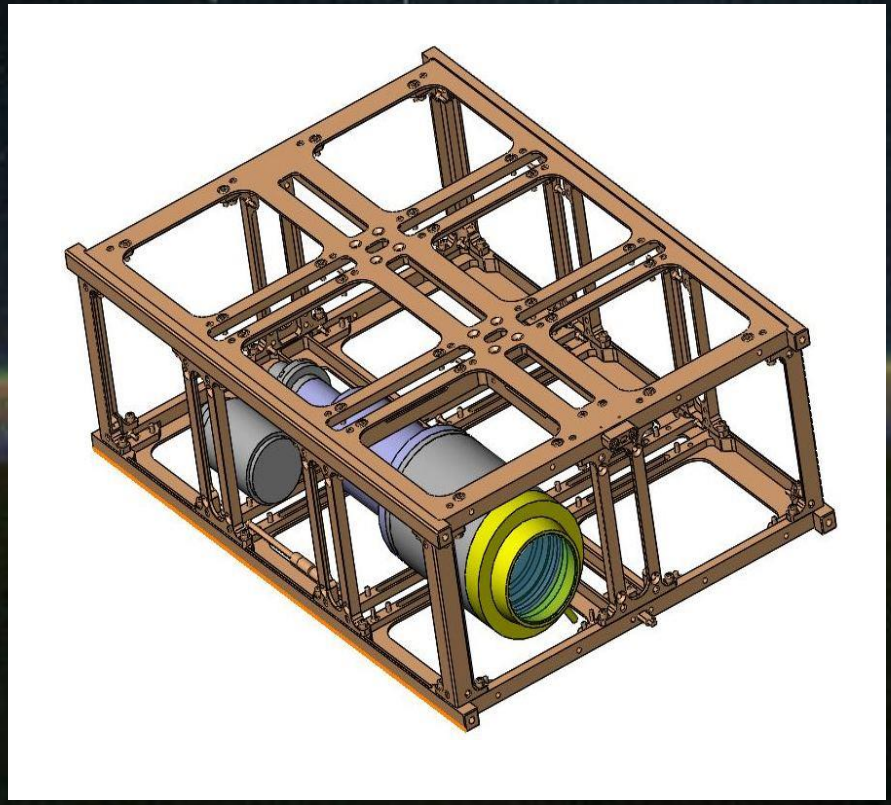



CUAD MicroSat
DWTS
TStar
LCER
Limb
Nadir
HATS

DWTS – Doppler Wind and Temperature Sounder

A new method of wind and temperature measurement

- Simple static limb imager
- Hi-resolution spectral scanning using Doppler shift
- From low earth orbit, it looks through a gas cell at the limb, perpendicular to the velocity vector
- The gas cell acts as a filter that scans atmospheric spectra with the same gas cell spectra
- Three imagers could provide wind and temperature from cloud top to 200 km on 10 km along-track spacing, *day and night*

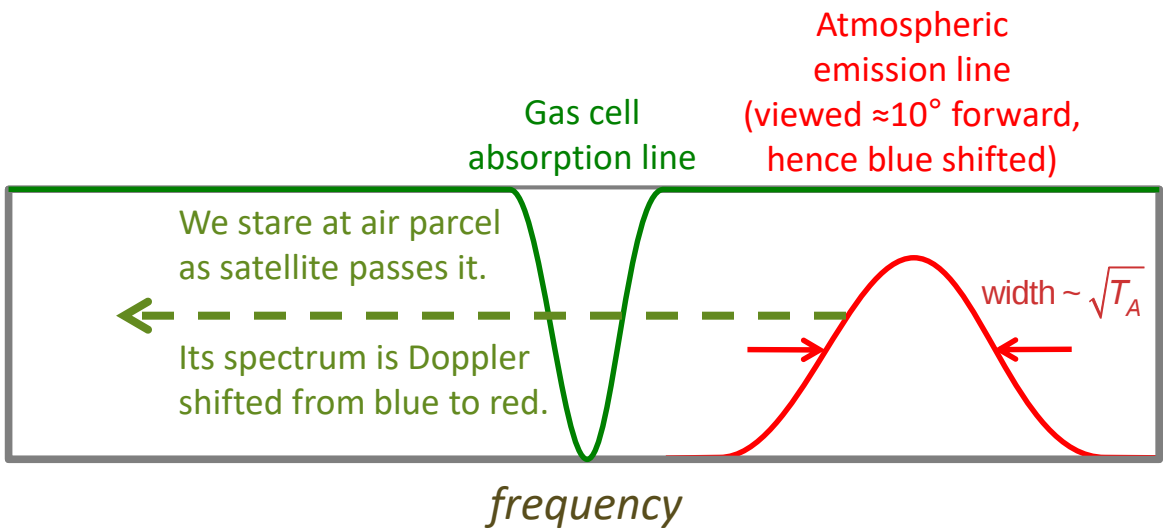


→ See DWTS tutorial at www.gats-inc.com/future_missions.html

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

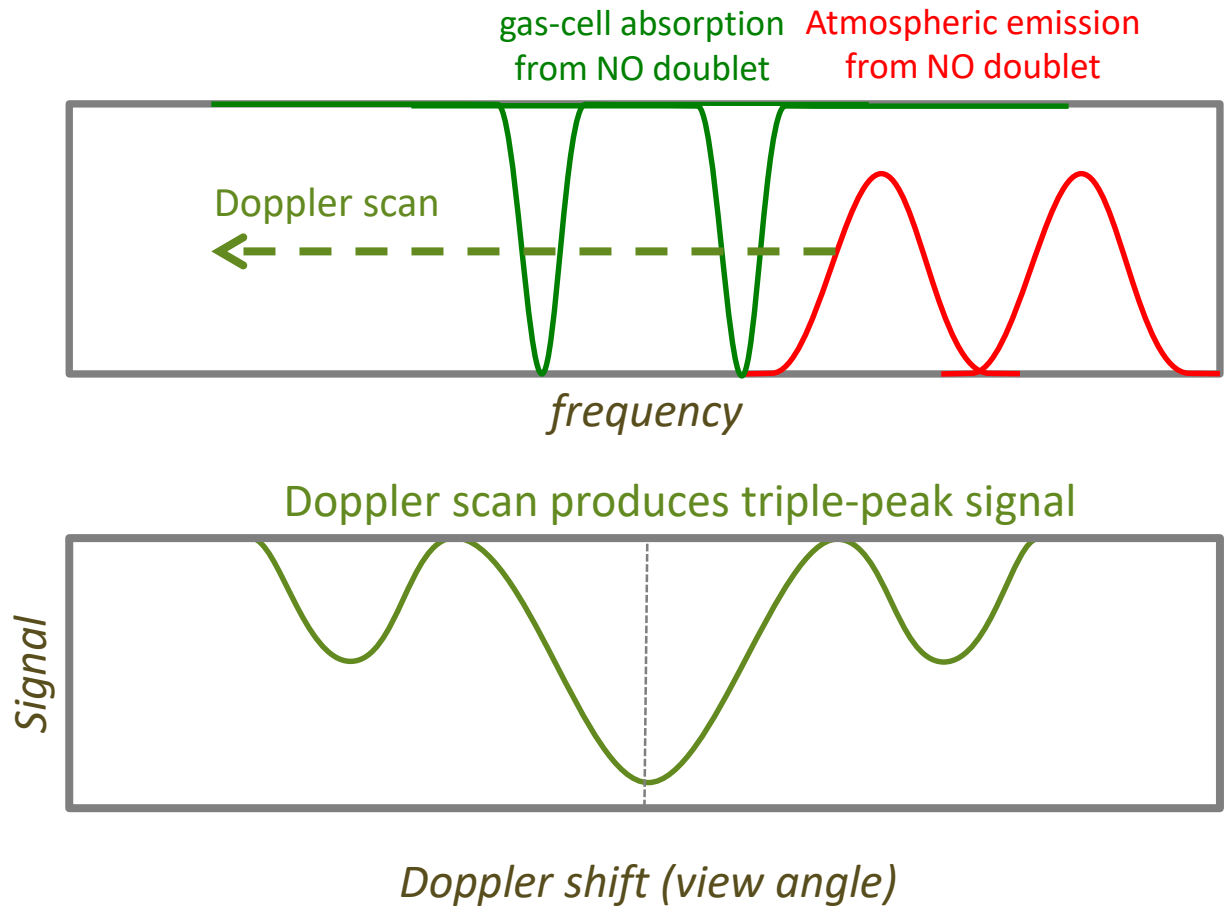
GSFC, Greenbelt, MD
December 1, 2017

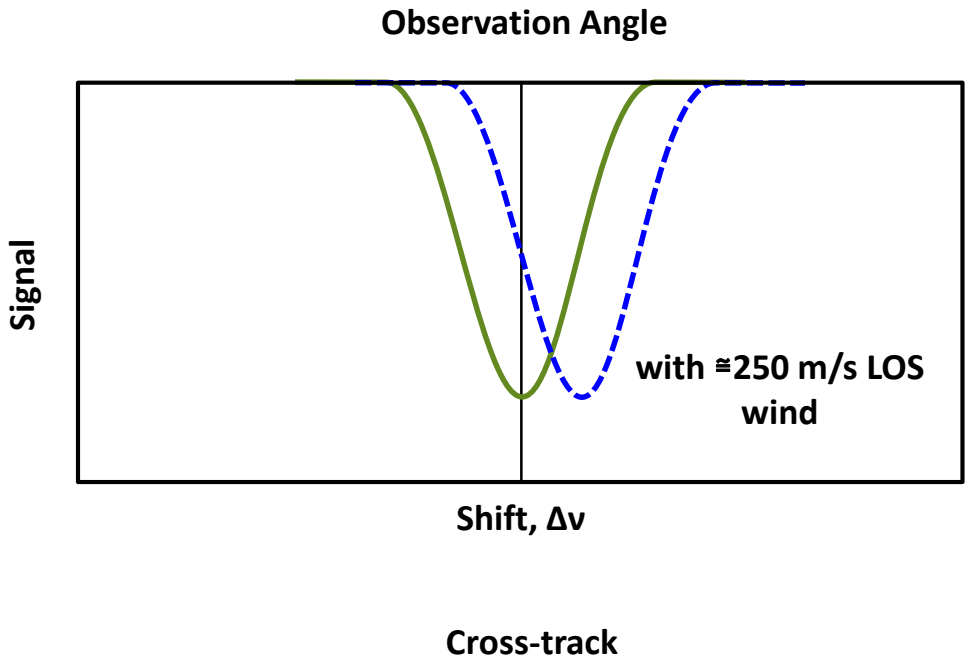
- **DWTS** One emission line example



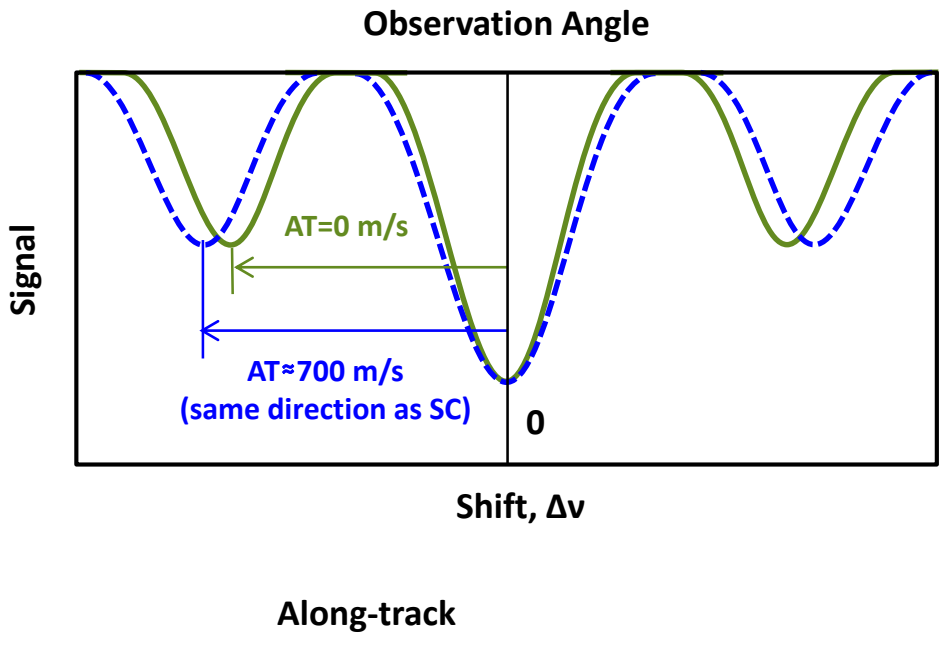
GSFC, Greenbelt, MD
December 1, 2017

- NO doublets produce multi-peak signal



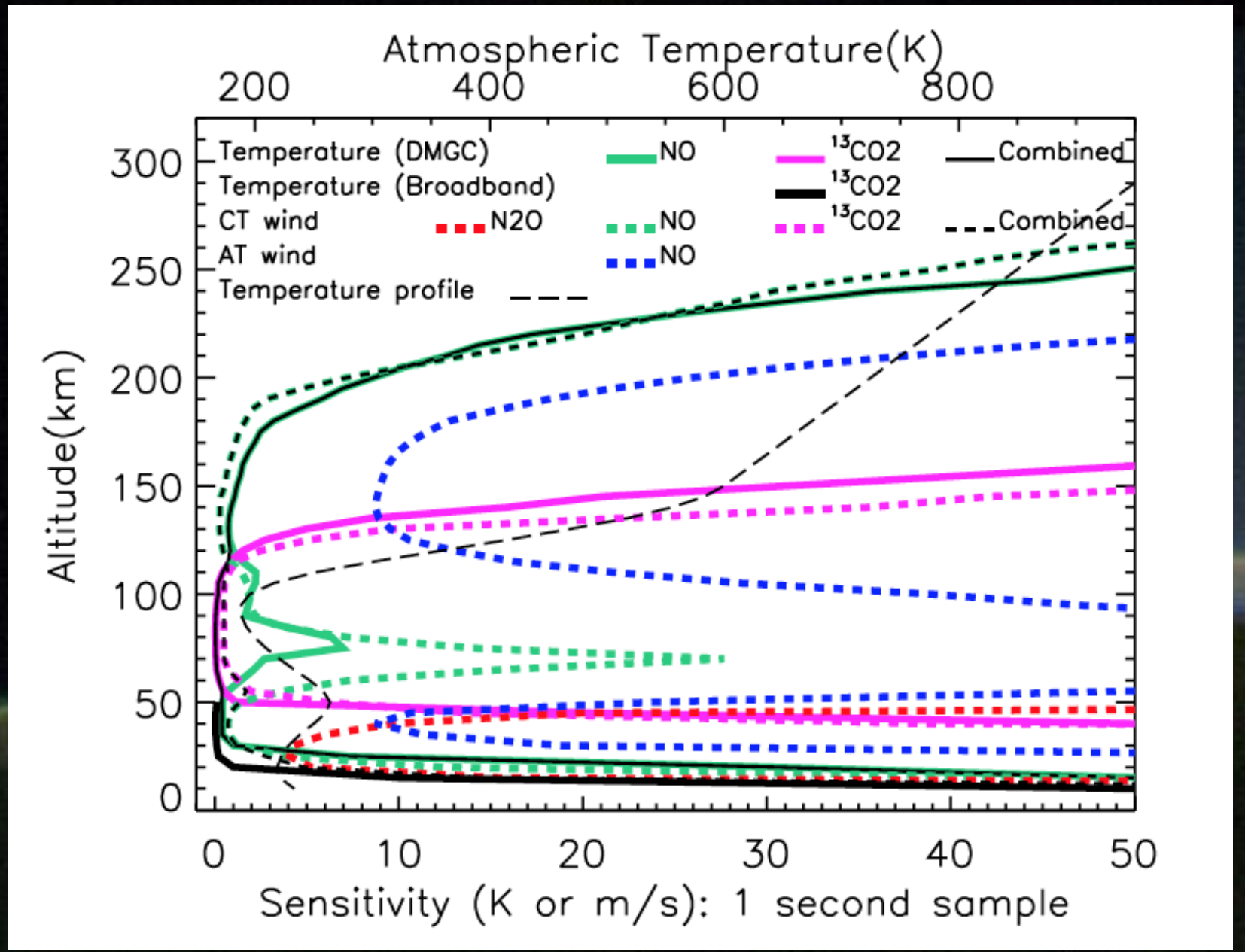


Cross-track



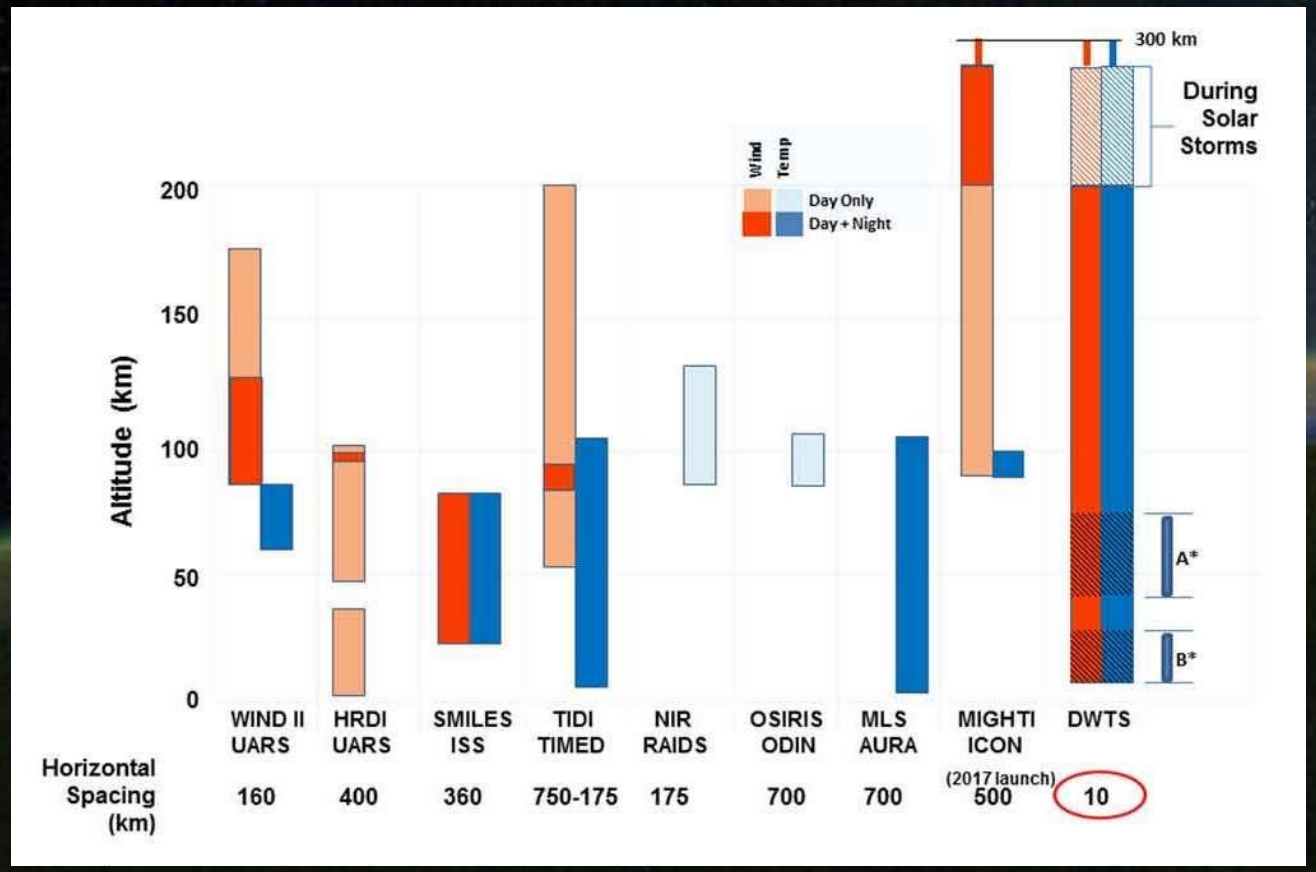
Along-track

GSFC, Greenbelt, MD
December 1, 2017


Atmospheric Temperature(K)
200
400
600
800
Temperature (DMGC)
Temperature (Broadband)
CT wind
AT wind
Temperature profile
N20
NO
NO
NO
13CO2
13CO2
13CO2
Combined
Combined
Altitude(km)
300
250
200
150
100
50
0
0
10
20
30
40
50
Sensitivity (K or m/s): 1 second sample

DWTS coverage

- Comparison to existing technology



Current measurements provide inadequate altitude, and day/night coverage

DWTS has an order of magnitude better horizontal resolution

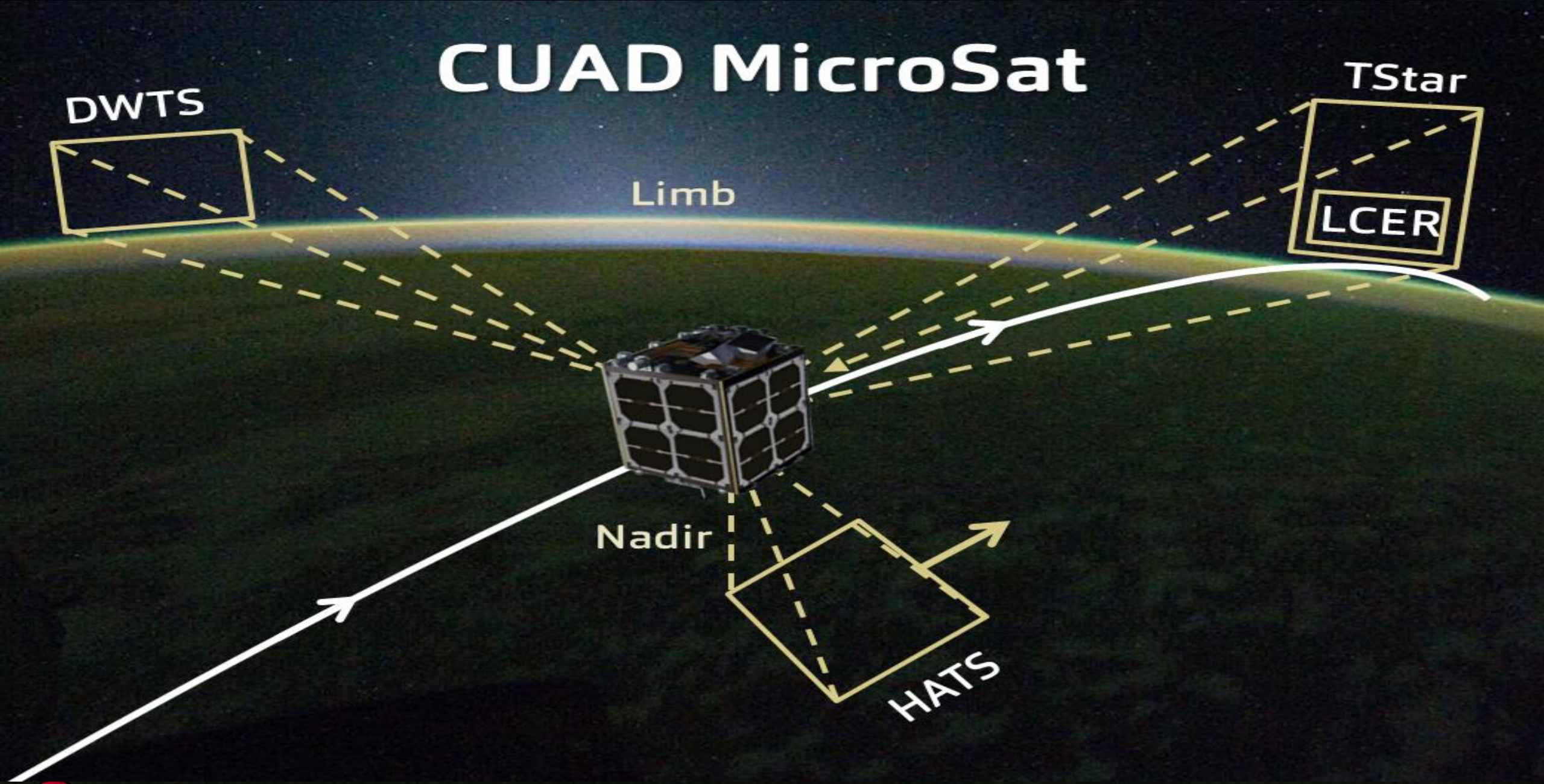
* Note that altitudes denoted by “A” or “B” would not be covered by a single channel (only NO) path finder instrument

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

GSFC, Greenbelt, MD
December 1, 2017

DWTS wind and temperature, recognized value and feasibility

- Better medium range weather prediction
  - Stratospheric specification after SSW (Sigmond 2013 Nature)
- Value to NAVGEM (pers. comm, Steve Eckermann, NRL Especially due to DMSP failures)
- Assimilation to 100+ km makes a difference.
- Endorsed by NOAA SWPC (Tim-Fuller Rowell, Valery Yudin), NCEP (Louis Uccellini)
- Private communication with:
  - Paul Hays (through Carl Nardell of Google), U of Michigan
  - Gordon Shepherd, York University
  - William Ward, University of New Brunswick
  - Chris Englert, NRL (MIGHTI PI)
  - others
- Independent sensitivity validation by BATC engineer


CUAD MicroSat
DWTS
TStar
LCER
Limb
Nadir
HATS

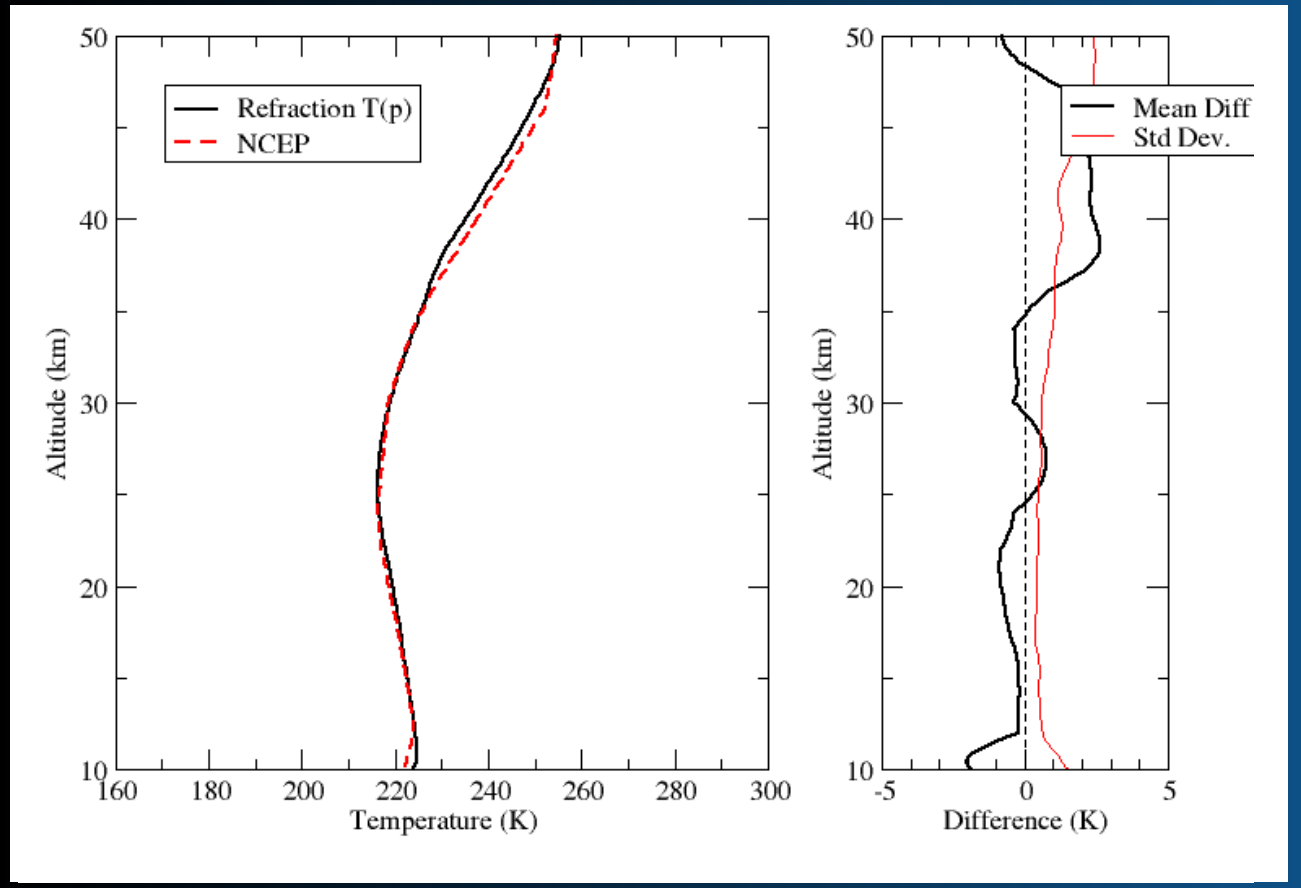
Temperature profiles used for CO_2 calibration (Method used with Tstar)

- Atmospheric refraction from vertical extent of distorted image
- Patented 2-point occultation method
- Can be accomplished with sun or moon or star fields!
- Requires very simple imager measuring in the visible spectrum
- Operational on SOFIE AIM

  Achieving 0.3 Kelvin accuracy

Statistical comparison of SOFIE temperature with NCEP

From edge tracking



2009-03-21 to 2009-03-26
SS-81.5 75 events

Refraction T from star field compression

Field of view as would be seen without atmosphere

Field of view as seen with atmosphere

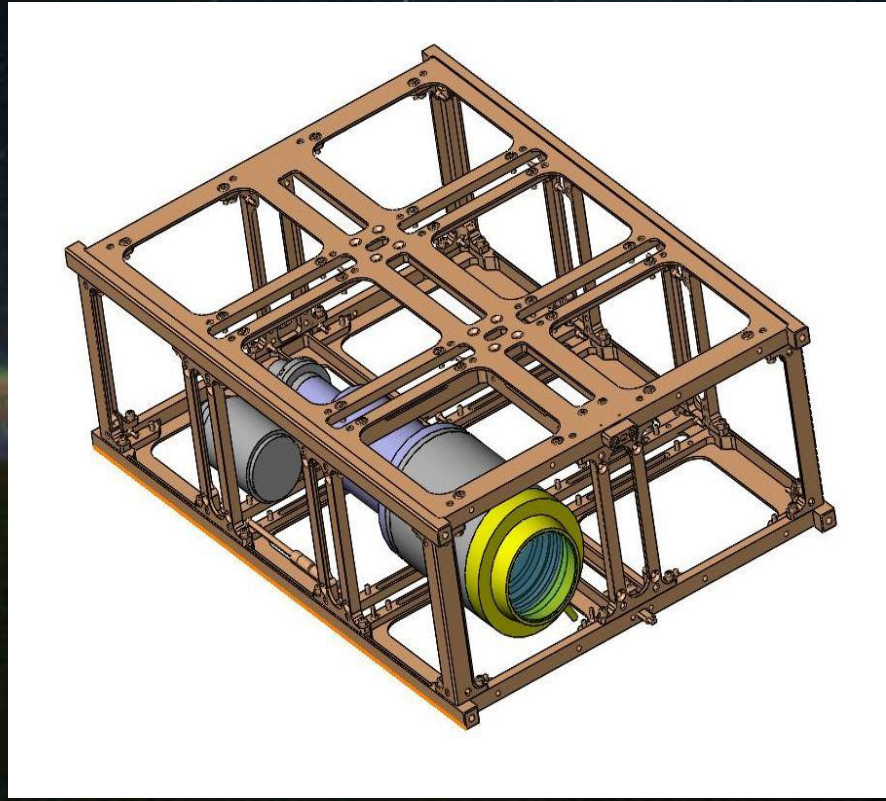
Progressive deformation due to refractive index of stacked layers of atmosphere affecting apparent altitude

GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

GSFC, Greenbelt, MD
December 1, 2017

LCER Limb CO_2 Emission Radiometer

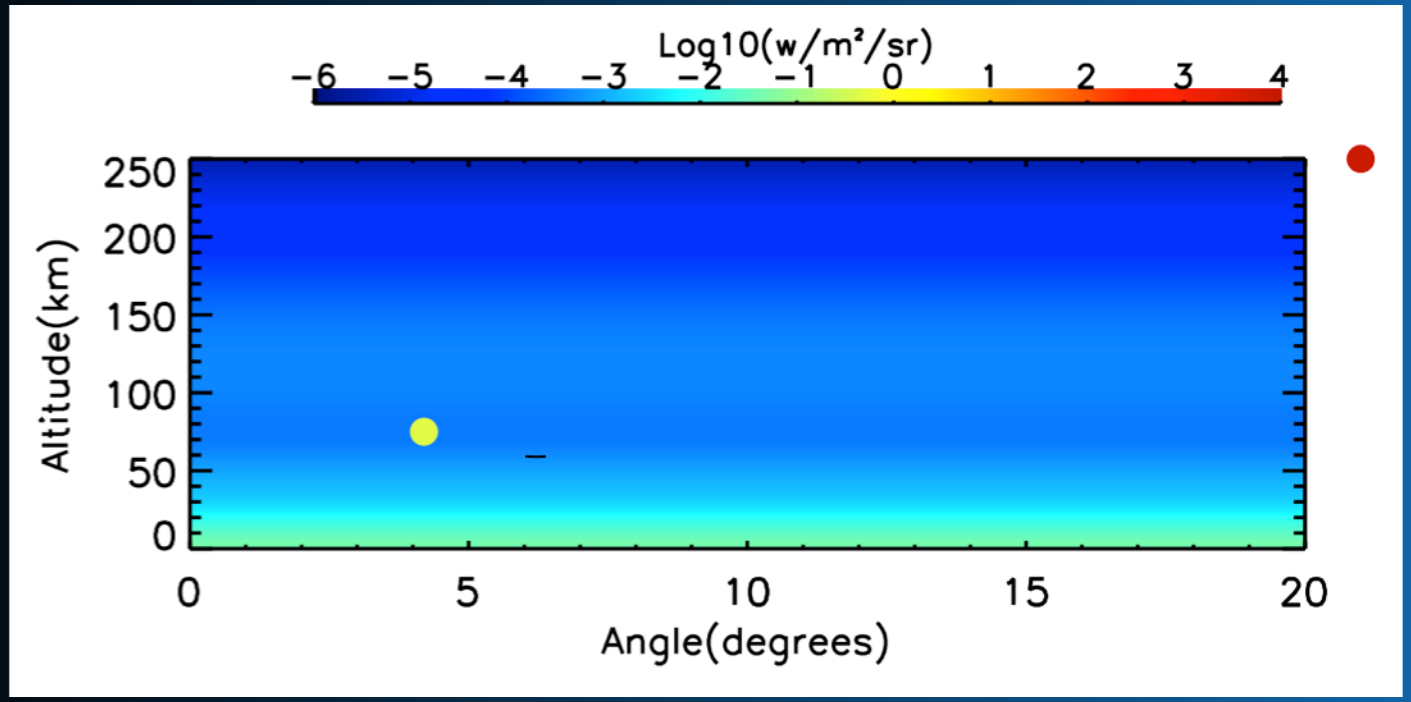
- Simple static imager of broadband limb emission
- Uses CO_2 emission and CO_2 concentration to retrieve Temperature profiles.
- Uses CO_2 emission, and T/P profiles from DWTS and TSTAR, to retrieve CO_2
- Temperature retrievals used to seed HATS retrievals
- Major challenge for limb imagers is stray light
  - Technology can now address that challenge



GATS GPI Gas Plume Imaging Ground·Air·Space BRANDYWINE PHOTONICS

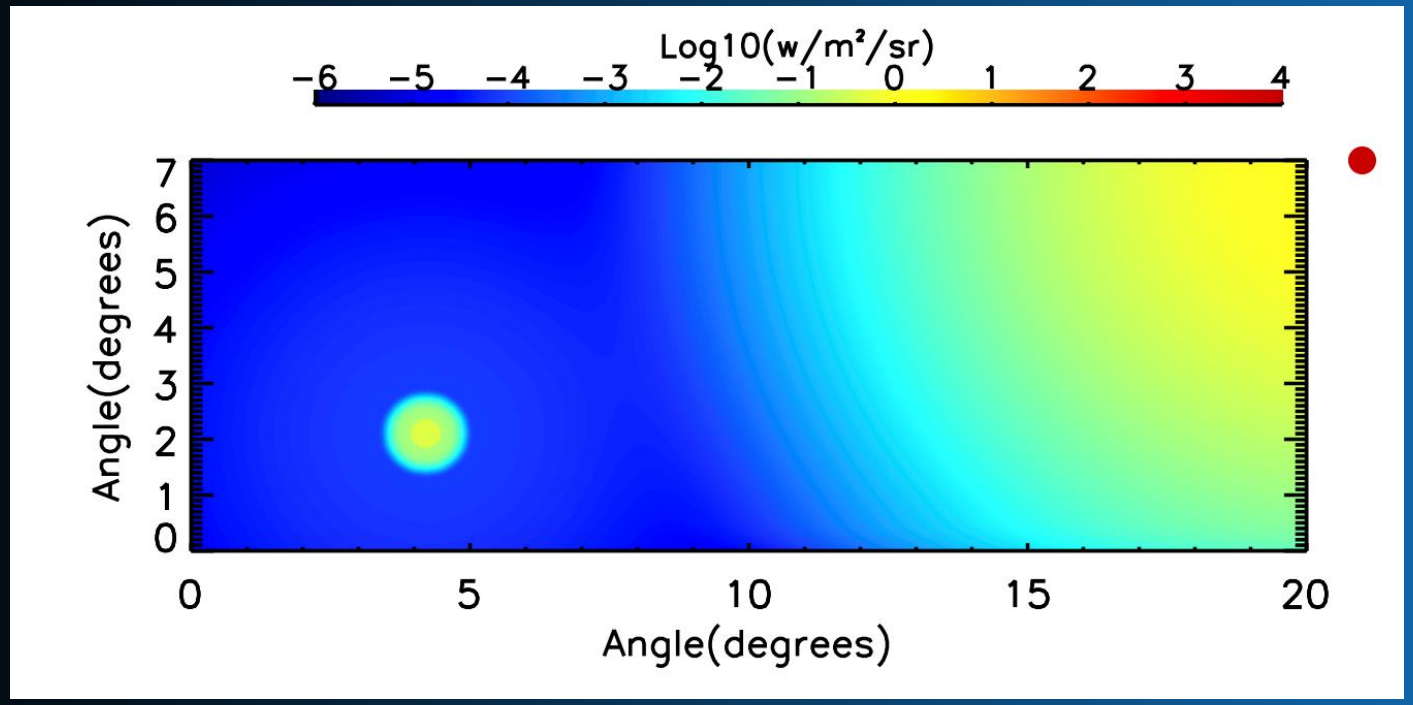
Stray light problem is now solved, thanks to FPA, ADCS & AR technologies

- Limb radiance in the DWTS Nitric Oxide channel at 5.3 µm
  - Atmosphere with perfectly resolved moon and sun (no stray light or off-axis energy)
  - Moon is as bright as entire lower limb
  - FPA measures nearly entire source function
  - Limb typically changes 3–5 orders of magnitude



Space view – With stray light

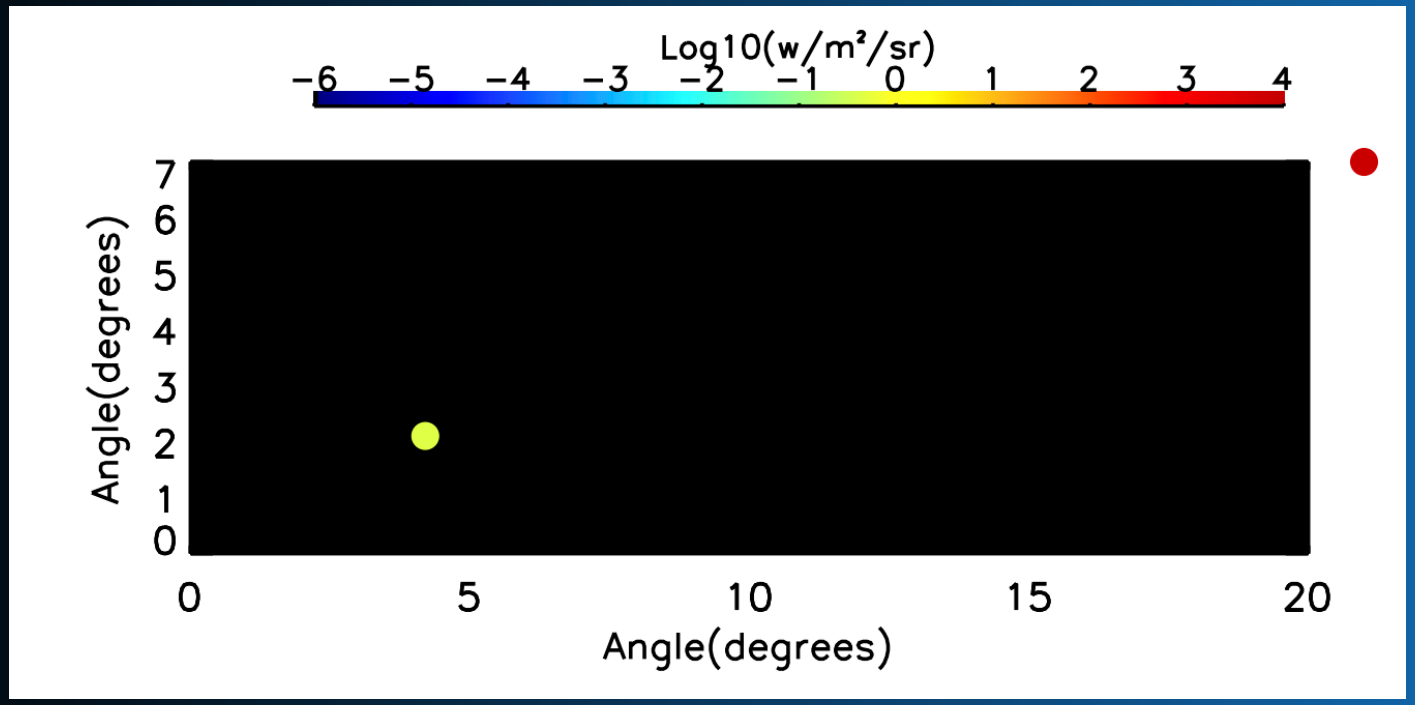
- Nearly perfect for calibrating BRDF and glare effects



Calibrate Stray Light with Space view

Space view

- Moon and sun in place, without stray light
- ADCS can direct scan
  - Creates calibration data
  - Need not directly observe the sun



Technology Enablers - Hardware

- ADCS precision and accuracy
  - Profile fidelity------critical to refraction and dlogR techniques
  - Calibration
    - Solar-glare
    - Lunar-Stray light-diffraction-Off-axis
- Cooling technology (active and passive)
- Downlink bandwidth (coming laser com)
- AR coating and Interference Filter quality
- Star tracker accuracy and precision
- Star maps for TSTAR temperature retrievals
- FPAs
  - S/N
  - Doppler scanning (DWTS HATS)
  - Calibration of stray light (provides full source function)
  - Refraction angle measurement for temperature (patented technique)
  - Simple static imaging systems
- Processors
  - On-board image processing power
  - On-board ADCS operations and orbital calculations

Technology Enablers – Analysis Techniques

- Doppler Scanning Gas Filter (DSGF) measurements (HATS, DWTS) (H*)
  - Limb T & Wind with unitless gas filtered measurements
  - Gas cell calibration as data bi-product from limb observations
  - High horizontal resolution Temperature from Nadir emission
- Temperature from refraction (bending angle) measurement
  - Multi-point celestial tracking (GATS Patent, SO*)
  - GPSRO
- CO_2 from DWTS and TSTAR temperatures and LCER emission
- Stray-light and glare calibration from solar, lunar and limb scans
- dlogR (unitless) analysis of limb emission profiles (L*)
- Off-axis response (PSF) from lunar scans (SA*)
- Absolute radiance calibration from limb observations (L*)
- A priori T from limb sounder for seeding nadir T sounder
- Dual filtering for out-of-band rejection (HI*)

- *Heritage instrument (L*-LIMS, H*-HALOE, SA*-SABER, SO*-SOFIE, HI*-HIRDLS)

Summary

- Global monitoring of upper atmosphere wind and temperature can now be done with very simple static imagers
- The synergy between the imagers will enable a 100% vicarious calibration scheme. No onboard calibration systems required
- Proven analysis techniques, novel new techniques, plus advances in ADCS, FPAs, Cooling Systems, Processors, AR Coating, Interference Filters, telemetry Communication Bandwidth and GPS systems make it possible.
-

Concluding Remarks

- Weather imprints its signature into upper atmosphere at large spatial scales, yet the dynamics remains mostly unobserved
- Simple Imagers, combined with Doppler Scanning Gas Filters, can fill the void.
- Will major forecast improvements follow?
  → *Evidence suggests it will*
- CUAD could monitor upper atmosphere dynamics (T,P and Wind, cloud-top to 150 km) with an order of magnitude improvement in resolution, latency and cost over past or proposed systems
- A pathfinder mission could be ready within 1 year for $10M