Instrumentation for accurate and sensitive remote sensing of the atmosphere

Henry Buijs

2016 Connaught Summer Institute in
Arctic Science: Atmosphere, Cryosphere, and Climate

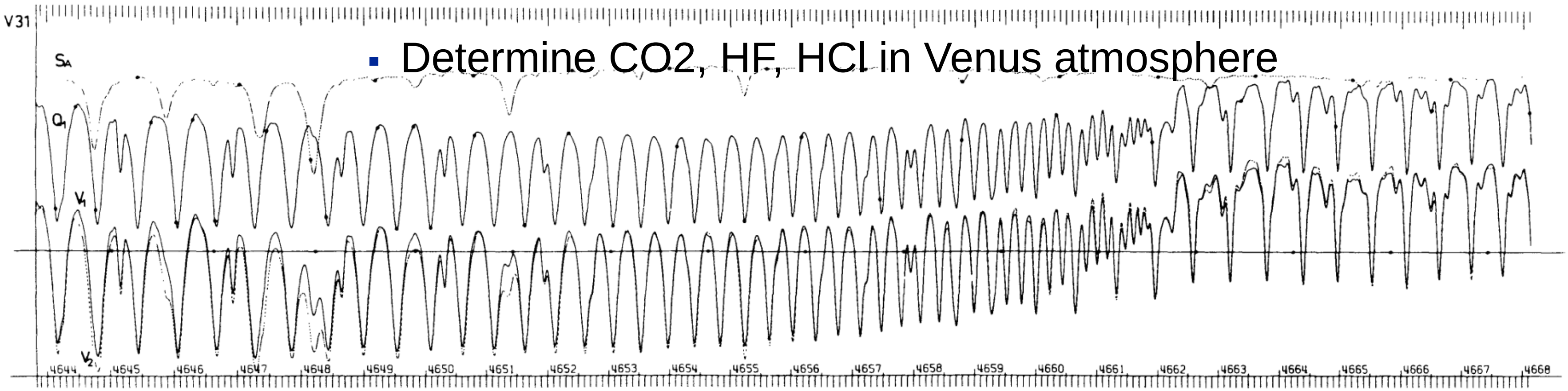
Content

- Remote sensing via Infrared Spectroscopy
  - Identify species by molecular structure Information
- In Ninety Sixties, Fourier Transform Spectroscopy (FTS) appeared unlikely candidate for remote sensing
- Detailed measurements of planetary atmospheres shows promise of FTS
- Early sensitivity advantages of FTS
  - SSEC ER2 campaigns with modified DA2 FTS
- A new advantage emerges
  - A new generation of weather satellites with Cris FTS
- Montreal protocol monitoring and other atmospheric research with ACE FTS on SciSat I
- TANSO FTS on Japanese GOSAT for greenhouse gas monitoring

Infrared Spectral Measurement of the Atmosphere

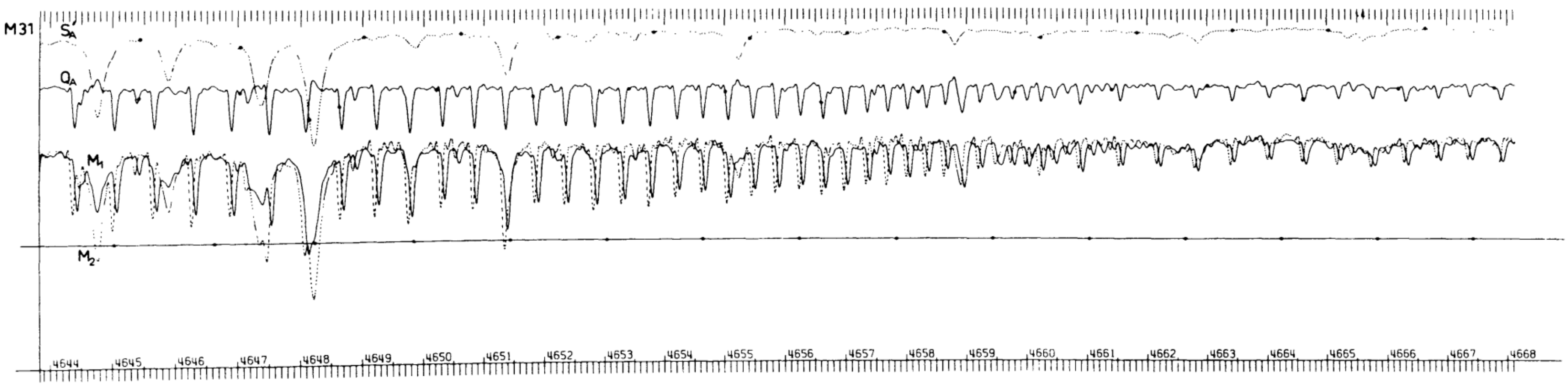
- Atmosphere consists of a mixture of gases with a wide range of gas mixtures, pressures and temperatures
  - Temperature distribution and changes between gaseous and liquid water greatly affect weather
    - Thermodynamic characteristics of atmosphere
- Absorption of solar radiation by atmospheric species and emission of thermal radiation drive temperature distribution
  - UV/Vis absorption, reflection and scattering also drive temperature
- The quest for increasingly detailed measurement of the atmosphere
  - From a perspective of personal experience using the technique of Fourier transform spectroscopy

Planetary spectra obtained with FTS (1968) demonstrate sensitivity and resolution (detail)



- Determine CO2, HF, HCl in Venus atmosphere

- Solar reflection, short wave IR



P. Connes, Aspen conference (1970)

Quest for sensitivity and field portability

- Measurement of weak night airglow from balloon platform (1962)
  - OH and O_2 emission in 1.2 to 2.27 um region

1038 CANADIAN JOURNAL OF PHYSICS. VOL. 42, 1964

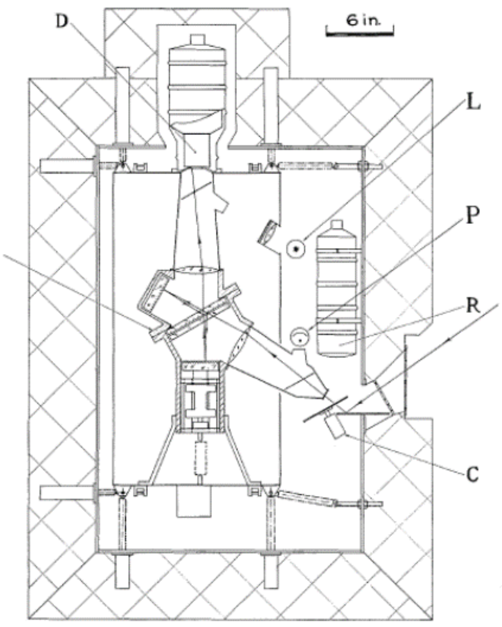
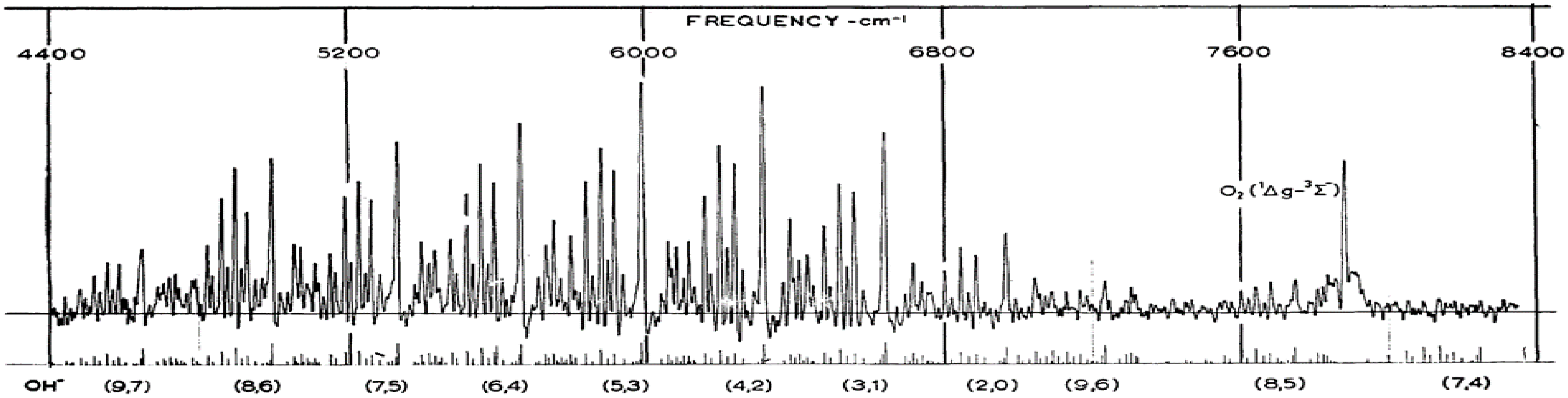


FIG. 1. A cross section of the high-altitude interferometer. I, interferometer; D, cooled infrared detector; L, helium discharge lamp; P, photomultiplier; C, reflective chopper; R, cooled black body reference source. The interferometer is enclosed in a thermostatted box, insulated by six inches of styrofoam.

Hand digitizing of paper traces of interferograms
Spectrum compute time 40 min. on IBM 7094 (Pre FFT period)
All transistor electronics (pre-IC)
Balloon flight operations, Valcartier, QC.



FTS shows high resolution and high sensitivity capability

- In sixties, sensitivity demonstration of FTS was conclusive
  - Many implementation problems were faced
    - Digitization of interferogram signal is needed in order to compute spectra
      - Sampling timing schemes were primitive
    - A monochromatic reference light source is ideal for sampling
      - Provides accurate wavelength calibration of complete spectra
      - Lasers solved this problem
    - Fourier transform computation was challenging
    - The fast Fourier transform (FFT) algorithm was a great advance
    - Moore's law in computing capability was also great advantage
    - The Michelson interferometer is a delicate instrument
      - How to make it work well under harsh field conditions

Opportunities for remote sensing of the atmosphere

- Ozone appears a fragile part of the atmosphere
  - Postulate that a fleet of SST could damage the ozone layer (1971)
  - Discussed the idea of continuously servo aligning a simple interferometer (Pierre Connes)
- A prototype Dynamic Alignment (DA) interferometer was built at Universite Laval for 0.006 cm-1 resolution
  - Attempt to measure stratospheric NO by ground based solar spectroscopy

Feasible in cold dry weather in Quebec (1971)

Reduced interference by water vapor

- Formed Bomem Inc 1973

Dr Wayne Evans, AES visits Bomem October 1974

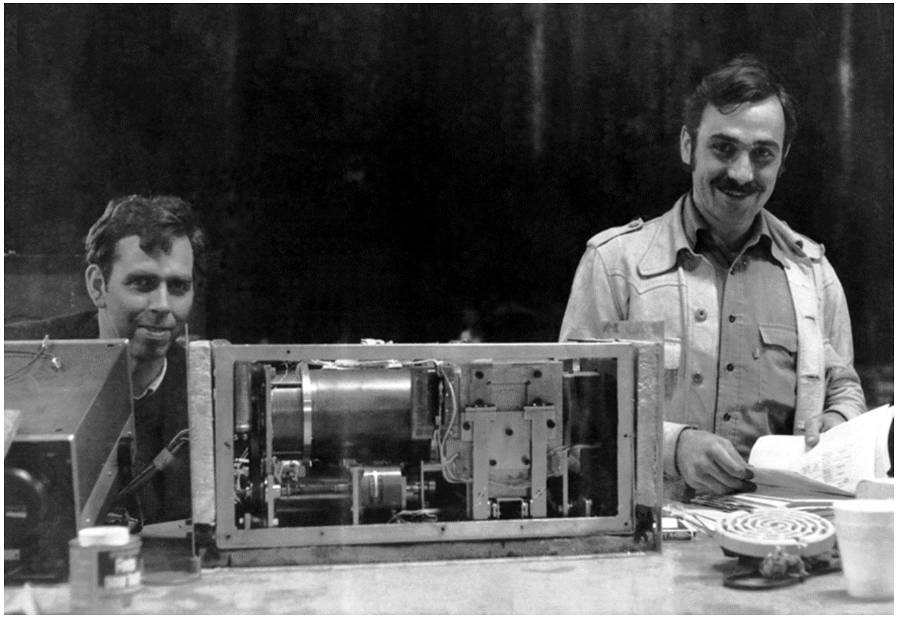
Invitation to participate in balloon campaign to study ozone chemistry

With dynamically aligned interferometer For balloon borne solar spectroscopy

Must fit in 25 x 25 x 50 cm space

Near Failure of Bomem Inc. (May 1975)

- After constructing interferometer, instrument does not work
  - Time and money invested for nothing? No!
- Ship instrument and all tools to Saskatoon balloon flight operations
  - Continue debugging
  - Some evidence of operation
    - Wayne accepts the instrument
- Two Balloon flights with no results
- In depth post mortem and design improvements fall 1975



Back on Track

- Opportunity to participate in balloon campaign in Fairbanks Alaska
  - U of Denver, Dr. Dave Murcray
- Good results, May 25 1976
  - Measure vertical profiles of HCl and HF
- Murcray uses large scanning grating spectrometer
  - At first skeptical about FTS
  - Seems too small for resolution claim
  - Later was convinced and purchased many units

Important Results in Alaska

- HF and HCl are sinks for F and Cl
  - Mixing ratio has peak in ozone region

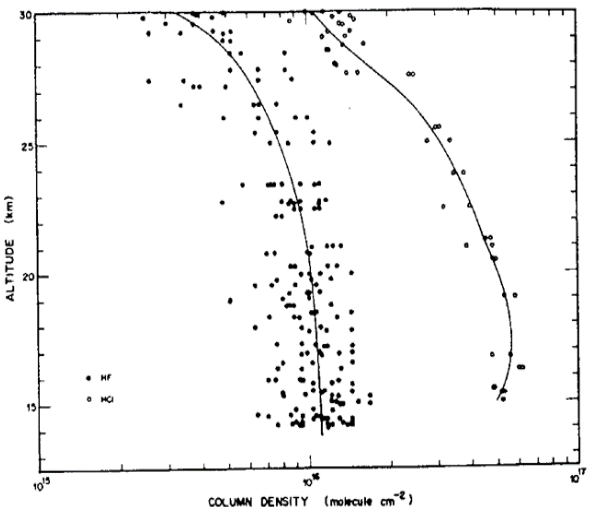


Figure 3. Column density values of HF and HCl plotted as a function of the tangent height.

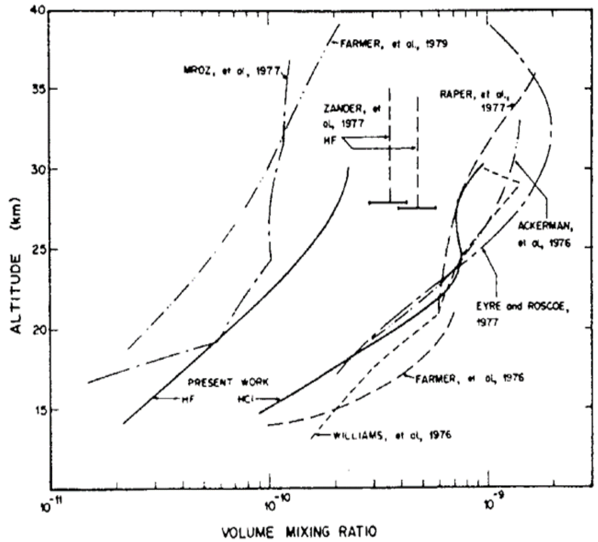
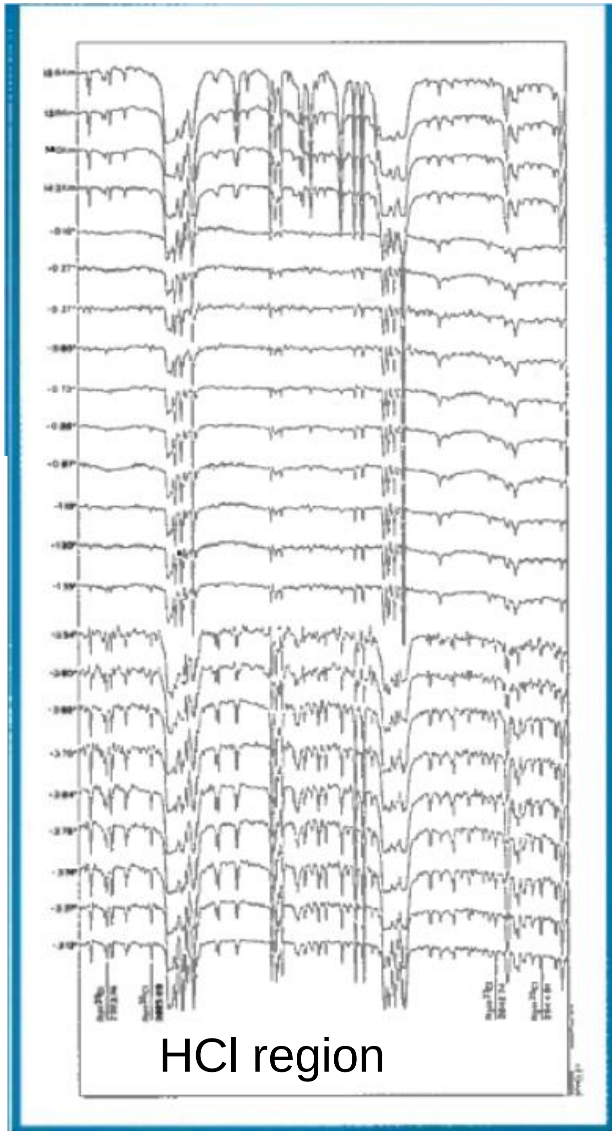


Figure 4. Volume mixing ratio determinations for HCl (all spectroscopic profile results) and HF (all measurements).



Bomem 1975 to 1980

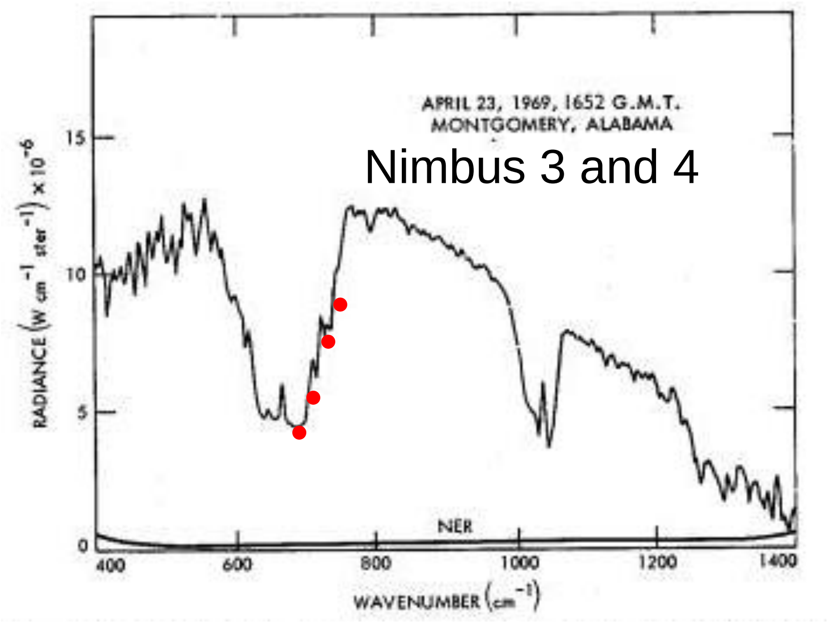
- Strengths and Weaknesses of FT-IR (1975)
- FT-IR has a tremendous sensitivity advantage over dispersive spectrometers.
  - Multiplex (Fellget) advantage
  - Throughput (Jacquinot) advantage
- Interferometers are alignment sensitive
  - Mirrors must remain in preferred orientation to very small tolerances during scanning
  - Mirror tilt error of 1 micrometer from edge to edge changes spectral intensity by 10%
- Data processing can take weeks before spectra are seen

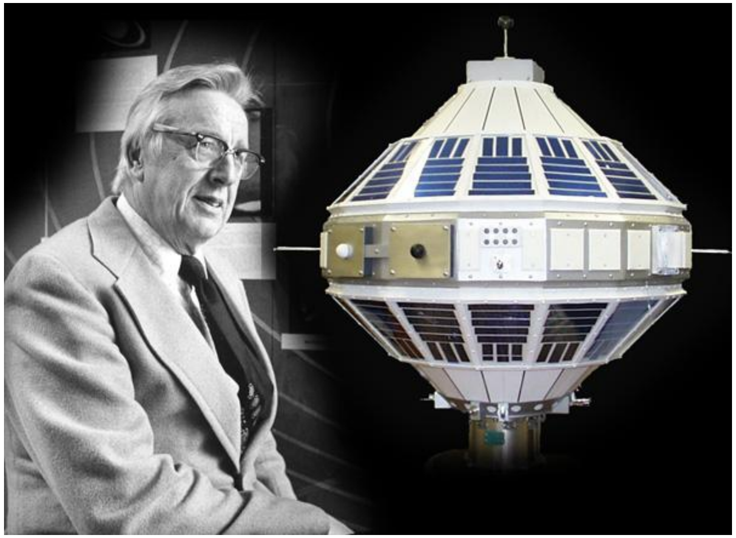
Bomem 1975 to 1980

- Develop a rugged dynamically aligned interferometer, the DA2
- At first for balloon borne solar spectroscopy
    - Active period because of concern for ozone depletion by CFC
  - Balloon campaigns in Yorkton Saskatchewan, Palestine Texas and Alamo Gordo New Mexico
  - Ground based solar spectroscopy at the South Pole (Murcray)
- Interest in other remote sensing measurements
  - A system is developed for the characterization of remote IR targets
    - Requires a rugged field portable instrument
    - Requires near real time visualization of spectra
      - Development of fast FFT processor

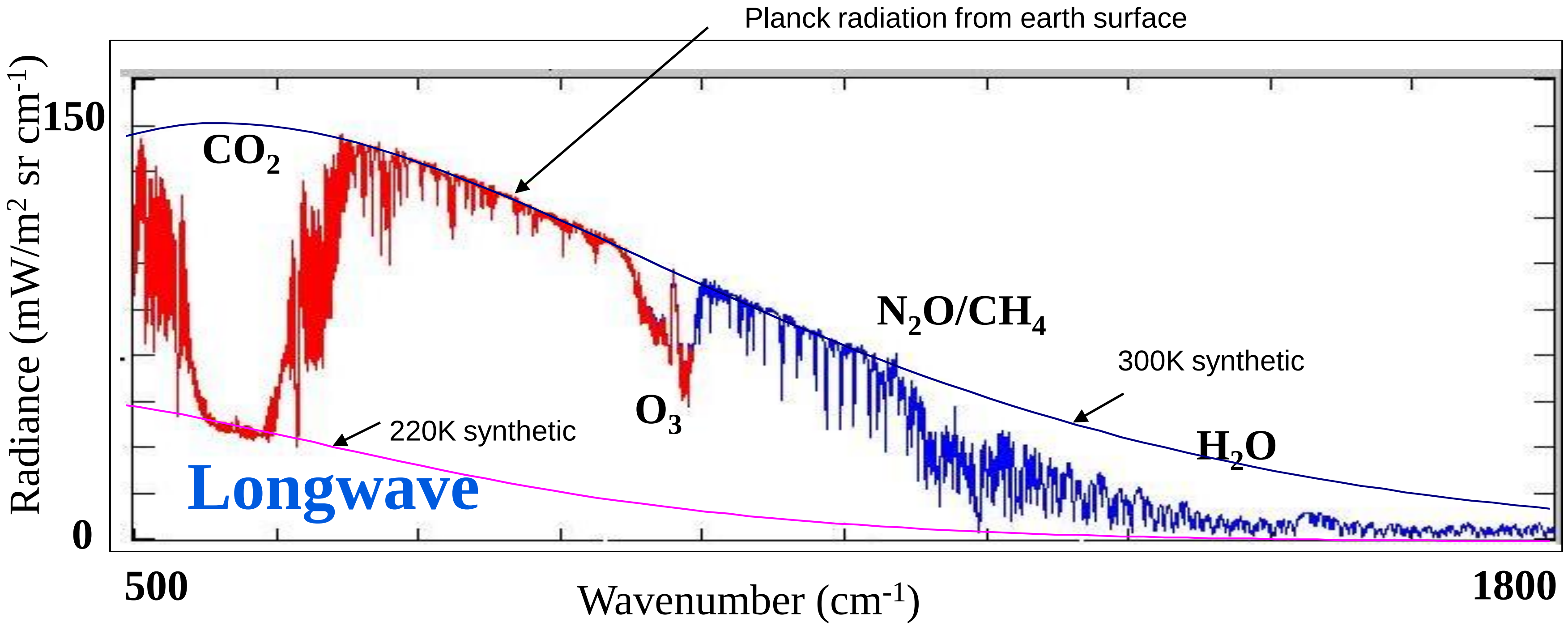
The era of weather satellites (Explorer 7 launched 1959) Verner Suomi, U of Wisconsin

- Filter type radiometer measures selected spectral regions (red dots)
  - To deduce temperature information for weather forecasting
- Early application of FTS for weather forecasting Nimbus 3 and 4 (1969)
  - IIRIS B (Hanel) and SIRS A (Wark)
    - Program discontinued





Actual Radiance emitted to space (scanning HIS on ER2)



Gas	*Symbol*	*% by vol*
Water Vapor (most abundant)	H_2O	0-4
Carbon Dioxide - it's on the increase in atm.	CO_2	0.038
Methane - it's also on the increase in atm.	CH_4	0.00017
Nitrous Oxide	N_2O	0.00003
Ozone	O_3	0.000004

Renewed investigation of FTS for weather sounding

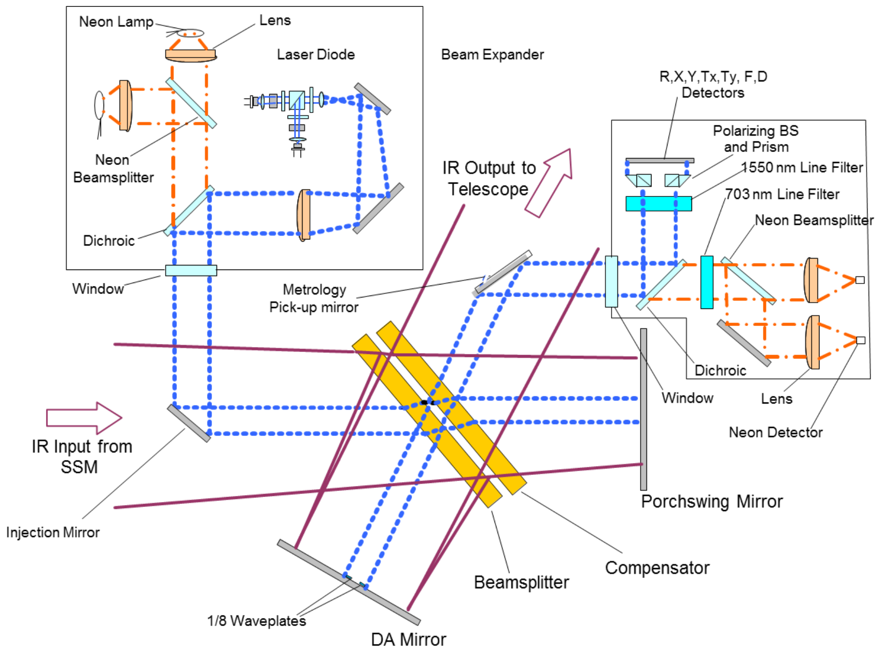
- U of Wisconsin Space Science and Engineering Centre (SSEC)
  - Considers high resolution full spectrum FTS for satellite weather sounding
  - 1983 Purchased DA2 and modified scan mechanism
    - Called HIS (High resolution Interferometer Sounder)
  - Operate on ER2 (U2) aircraft
    - Many year program still active today
    - To validate FTS for weather sounding
- FTS provides higher spectral resolution and very high radiometric accuracy
  - Permits higher vertical resolution in temperature, moisture, pressure profiles

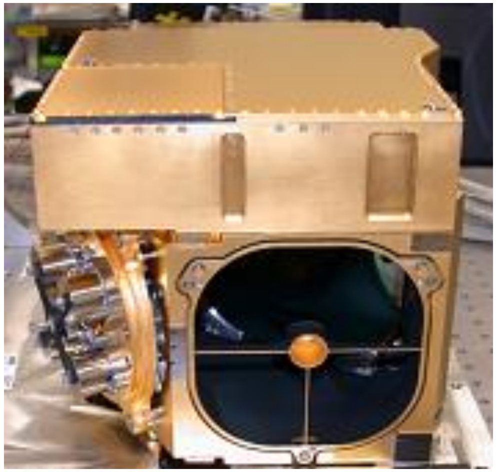
Renewed investigation of FTS for weather sounding

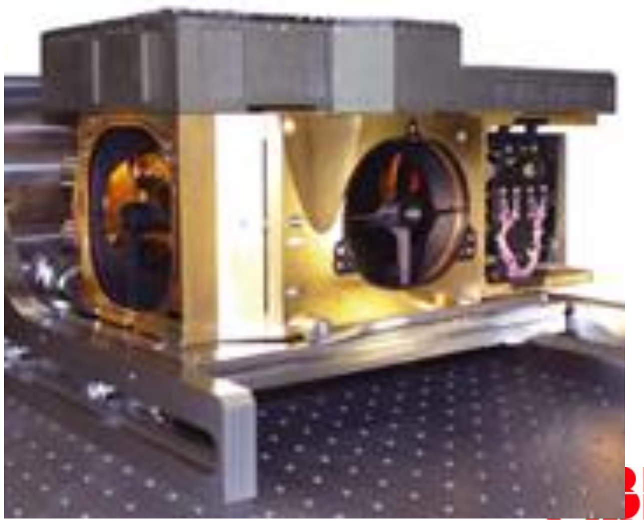
- U of Wisconsin Space Science and Engineering Centre (SSEC)
  - Research campaign with HIS on ER2
  - After 10 years (nineties) NOAA invests in new generation weather sounder based on FTS technology
  - In nineties FTS is not clear winning technology
    - Increases in detector sensitivity and detector array technology make dispersive approach comparable to FTS
    - Concerns about reliability of mirror scan mechanism in space
  - JPL builds a sounder based on dispersive technology (AIRS)
    - Many parallel detectors provide sensitivity and resolution
- More precise and reliable interferometer alignment developed by ABB/Bomem leads to precision advantage
  - Very precise line shapes
  - Very reproducible measurements
  - Frequent and accurate calibration

A new generation of weather satellites

- After more than 10 years of ER2 flights and several feasibility studies
  - NOAA supports development of FTS for the next gen weather satellite sounders in the NPOES program
    - The Cris project is started ~1995
    - PFM-1 launched on Suomi NPP October 2011
      - Performance is exceptional
    - PFM-2 delivered
    - PFM-3 being fabricated

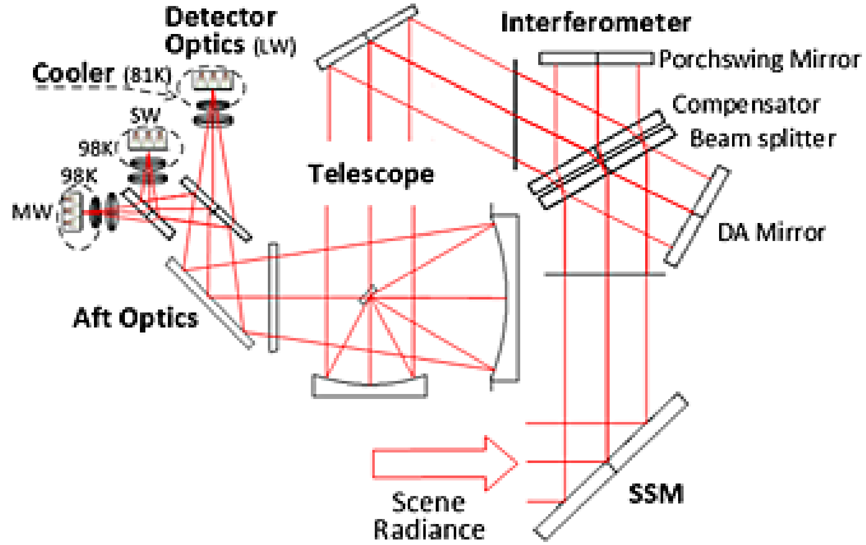


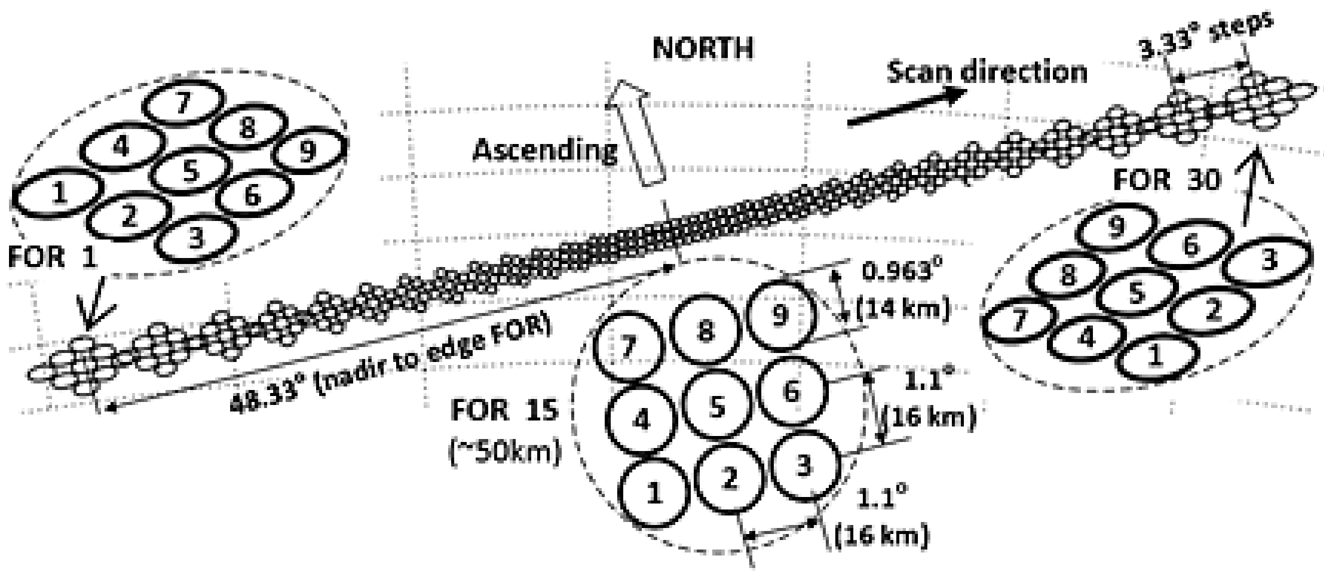




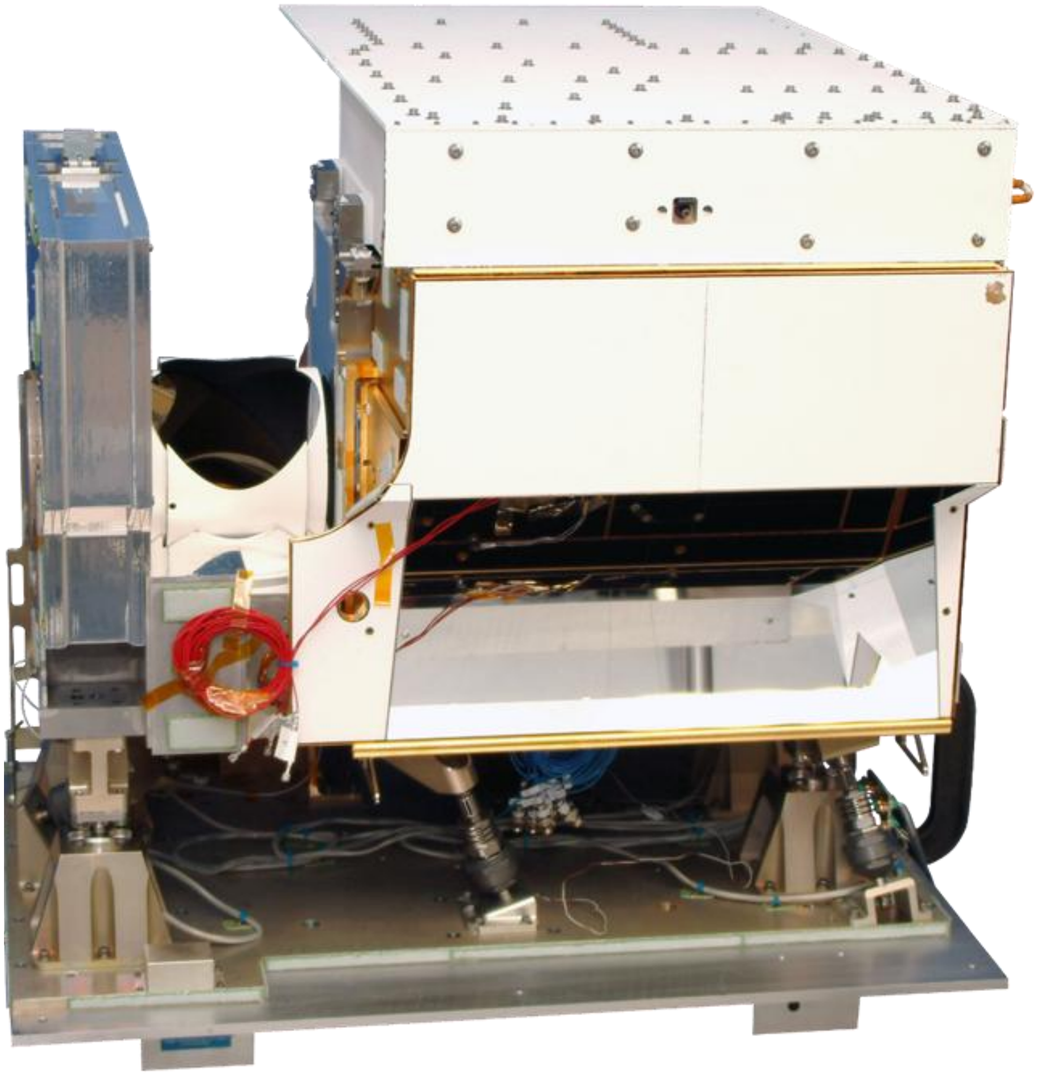
The Cris sensor

- The Cris sensor is provided with 3x3 detector arrays for three spectral regions
  - (27 detectors)
- To cover the globe it does five sweeps/s.
  - 45 spectra/s. for each of three bands
- SNR is significantly better than specified



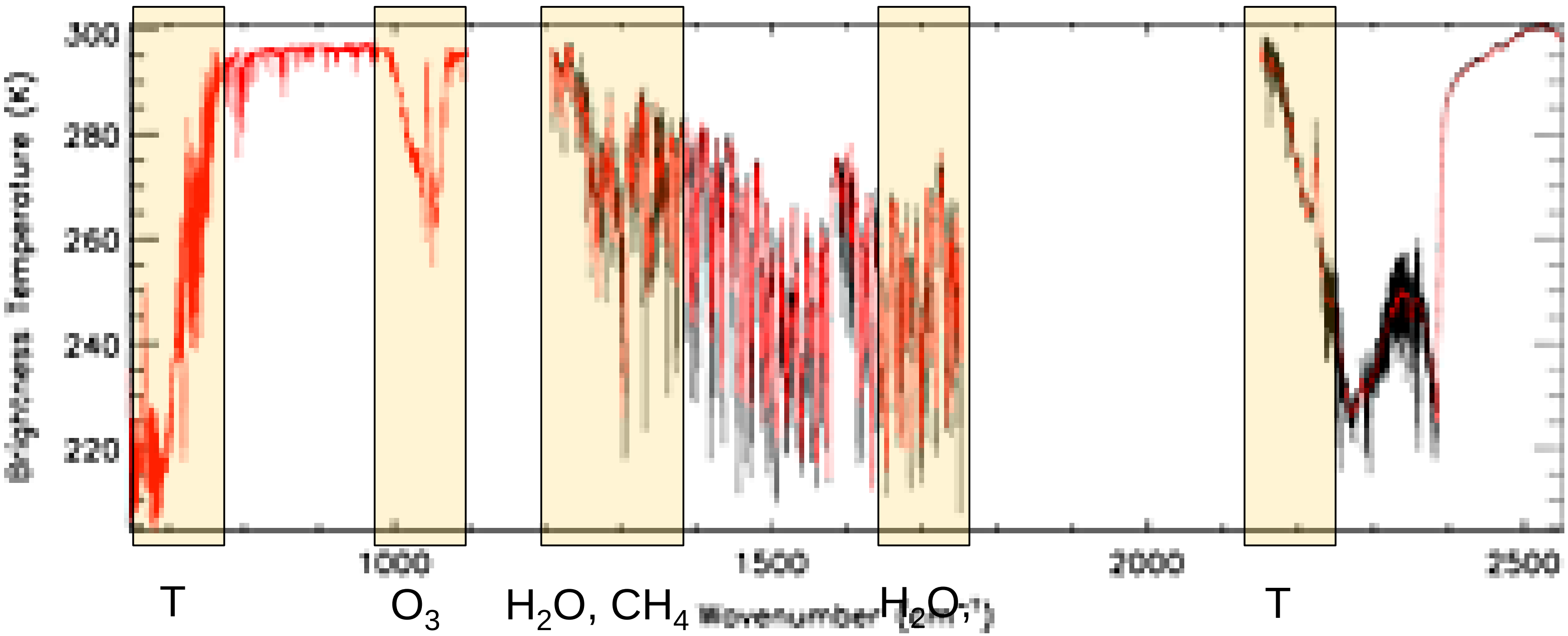


The complete Cris sensor



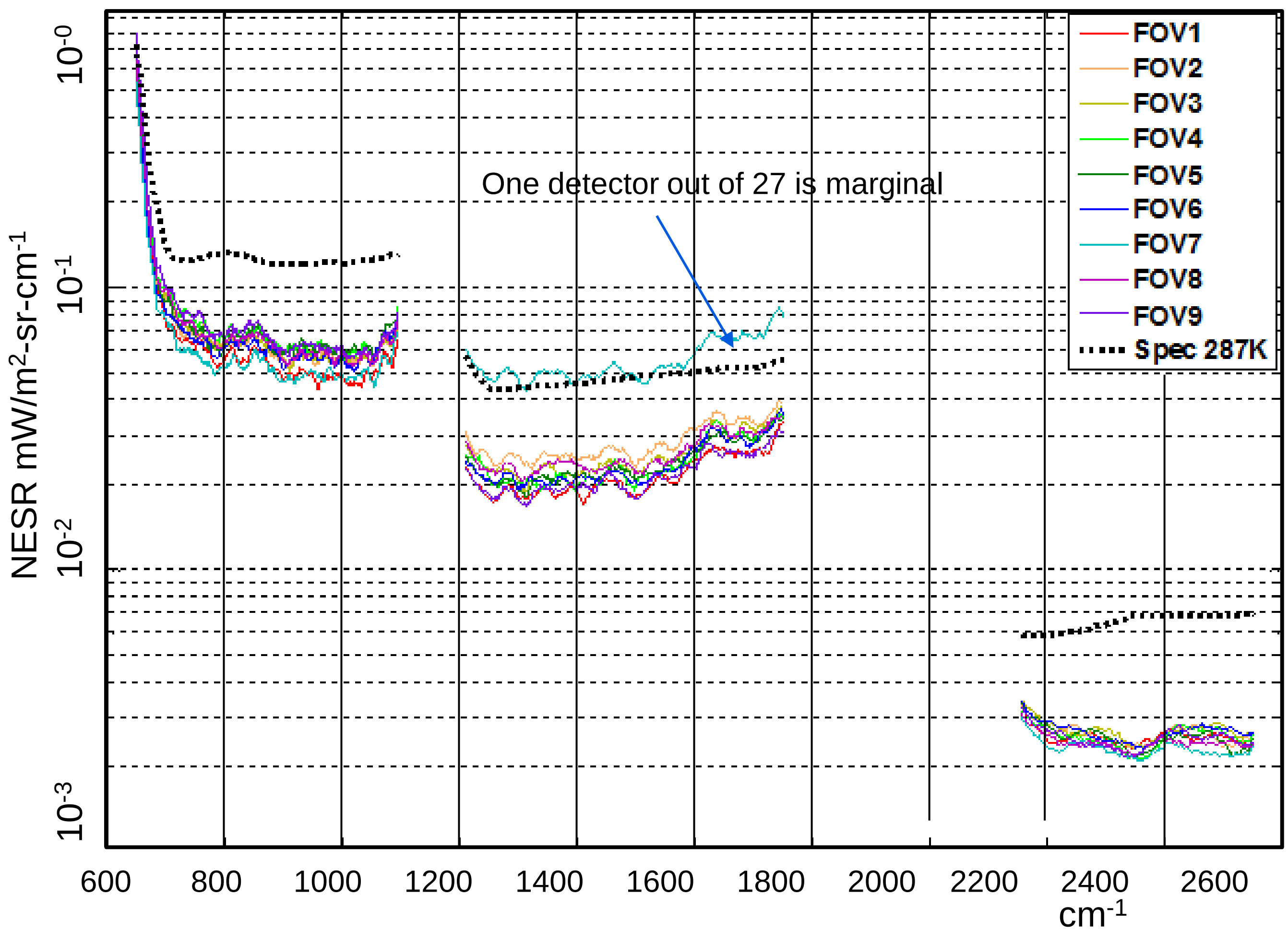
Cris Sensor performance

- Typical radiance spectrum measured in 0.2 s.
  - Expressed in equivalent BB temperature



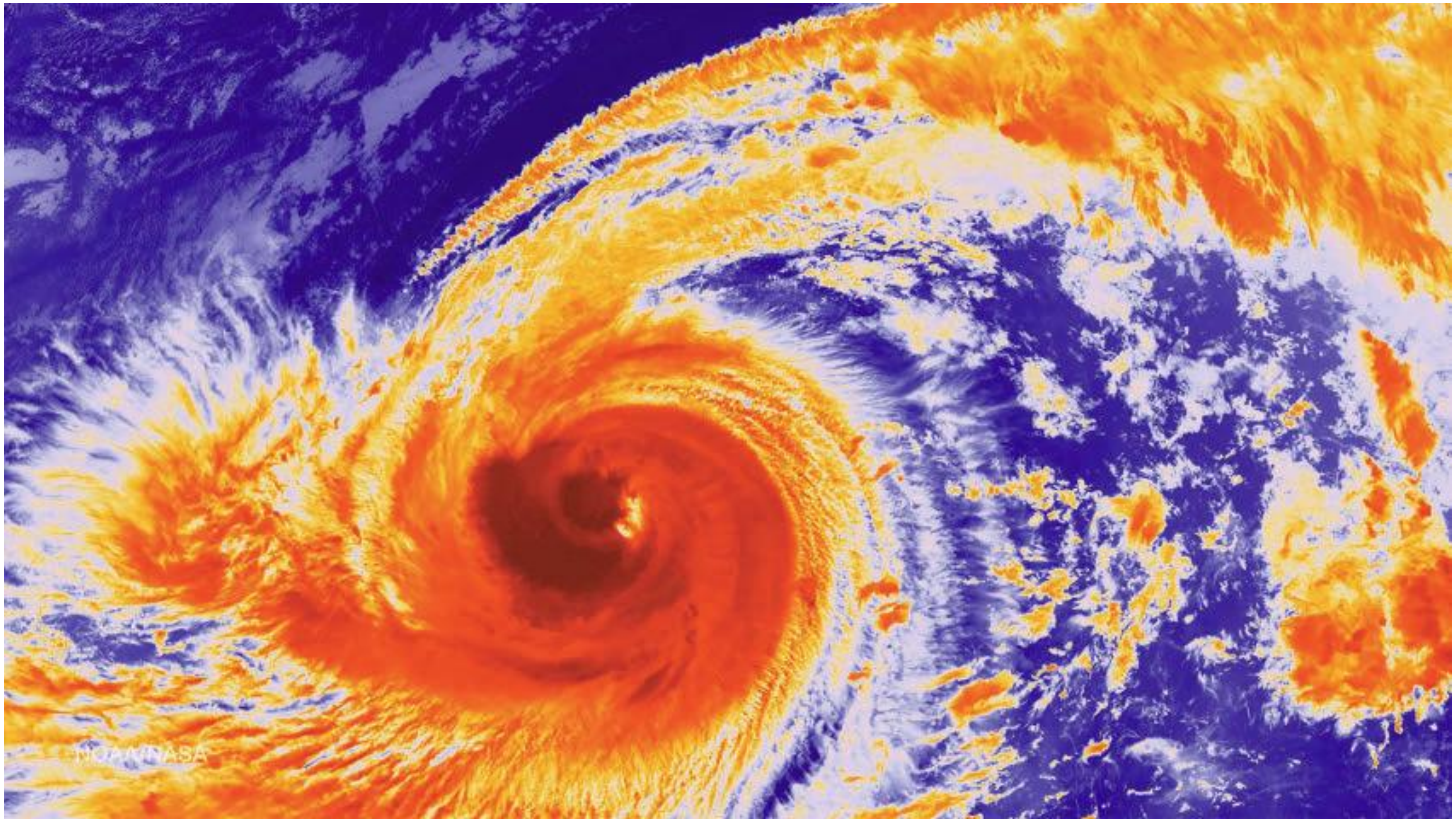
Cris sensor performance on orbit

- Outstanding low noise performance



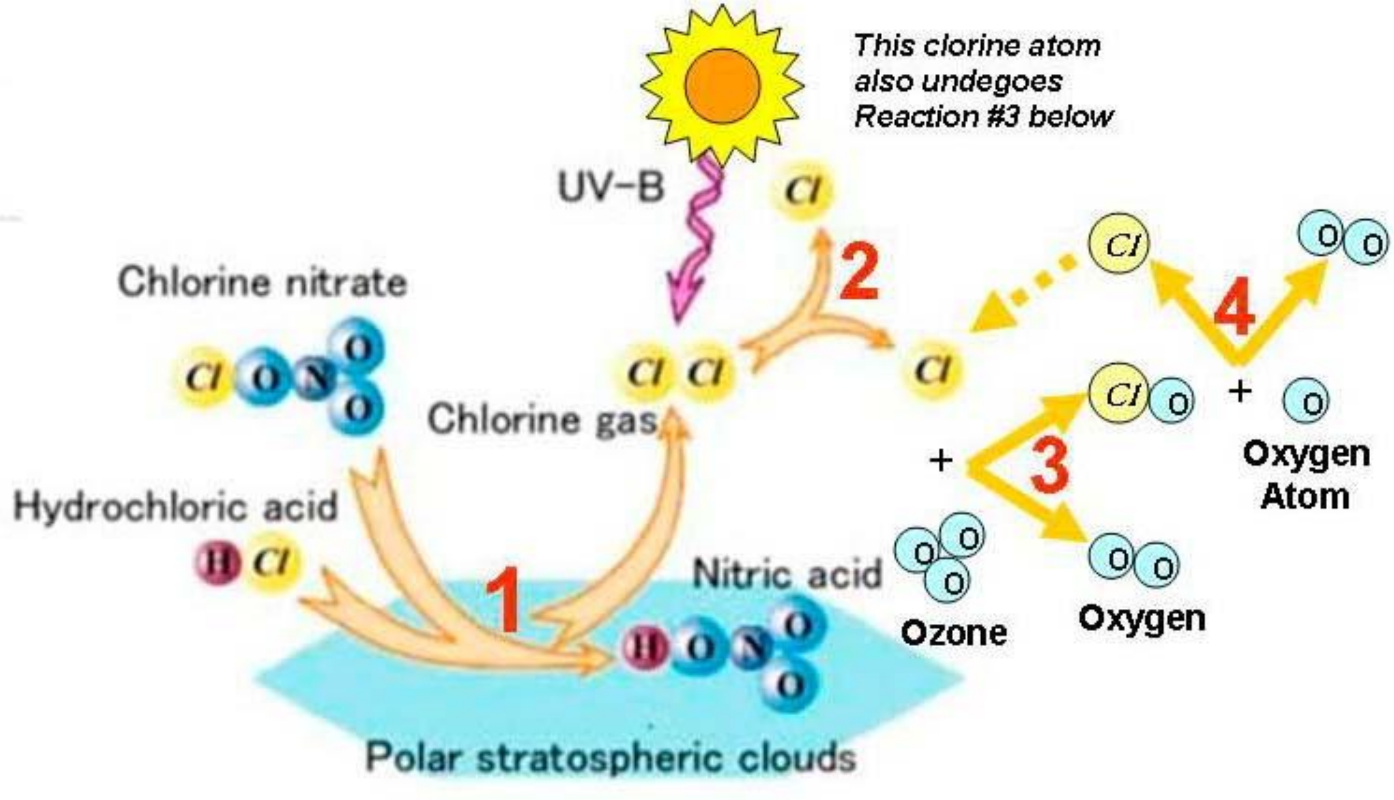
False color image of deep convective core of Typhoon Phanfone 650 miles south of Japan

- Each 14 km pixel provides a detailed radiance spectrum



A comprehensive understanding of Ozone chemistry
The Atmospheric Chemistry Experiment (ACE)

- The ACE project started in 1998
  - To better understand and quantify global ozone chemistry



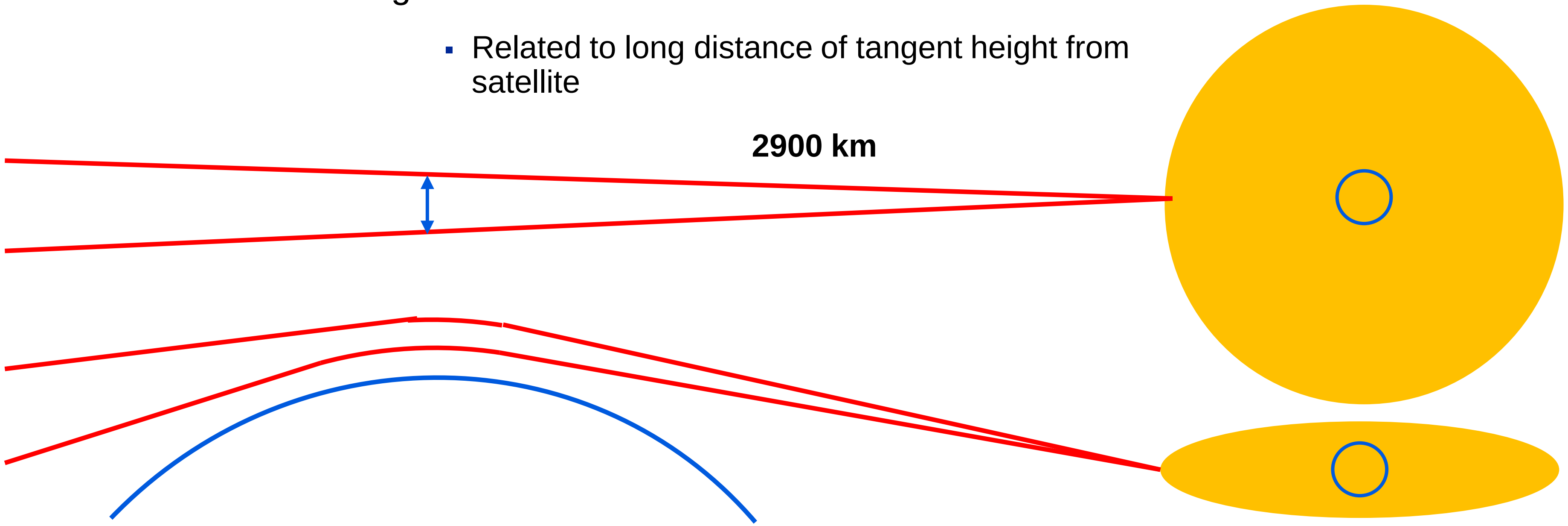
Inputs to ACE FTS design

- Spectral range 750 to 4410 cm-1
  - Based on need for measurement of essential stratospheric species
  - Covered with two detector spectral bands 750-1800 cm-1 and 1800-4100 cm-1
- Time to measure each spectrum 2s.
  - Causes some vertical smearing because of the fast rate of change of tangent height
    - At small beta angles tangent height changes ~ 1km/s.
- Atmospheric spectral lines are narrow
  - High spectral resolution and signal to noise ratio provide high sensitivity
    - High spectral resolution also provides better discrimination of spectral features
- Spectral resolution 0.02 cm-1 (spectral sampling interval)
- SNR objective >100:1

ABB

Parameters for ACE mission

- Vertical size at tangent height of received IR beam not greater than 3.5km
  - Dictates FOV of the sensor (1.25mr)
    - Use only a small portion of ~9mr solar disc
  - Deformation of sun image due to refraction gradient
    - Related to long distance of tangent height from satellite



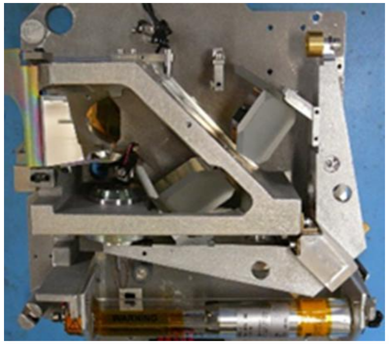
ABB

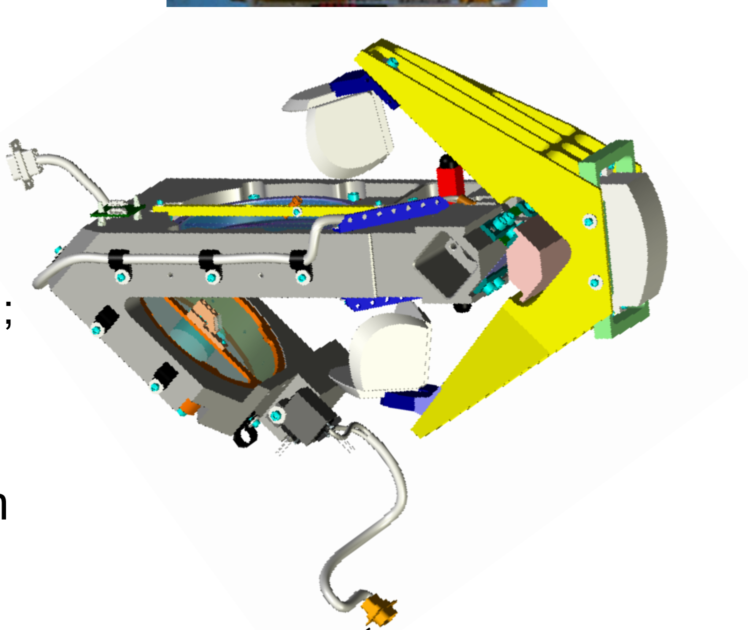
FTS design

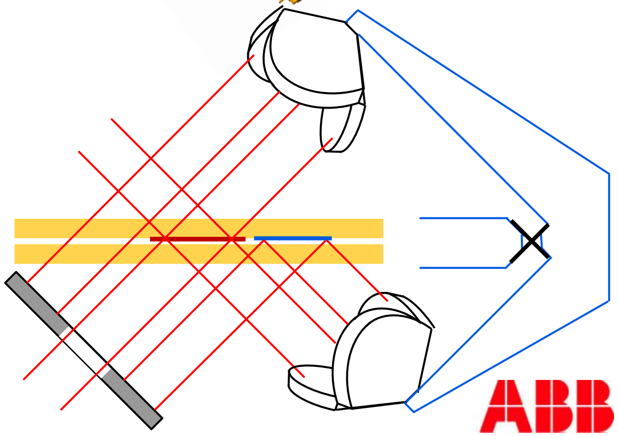
- Interferometer optical path difference (OPD) requirement is 25 cm from zero path difference for 0.02 cm-1 resolution (spectral sampling interval)
  - Double sided scanning has many advantages
    - Total OPD range is 50 cm
- Challenges:
  - How to accommodate in a small volume
  - How to insure uniform modulation (alignment) over the 50 cm OPD range
    - Impact on ILS
  - How to provide constant scan velocity in a space environment

FTS design

- Solutions:
  - Double pass IR beam and scan both arms of interferometer
    - Provides ratio of 1/8 mechanical/optical scan
  - Use tilt and shear compensated interferometer design
    - “Double pass with single return mirror” design; Schindler, JPL
      - Heritage from ATMOS
  - We have more than 10 years experience with double pendulum with flex pivots
  - Flex pivot mounted rotary scan
    - Has no friction or stiction and operates in high vacuum
    - No performance degradation over time
  - Well suited for satellite mission



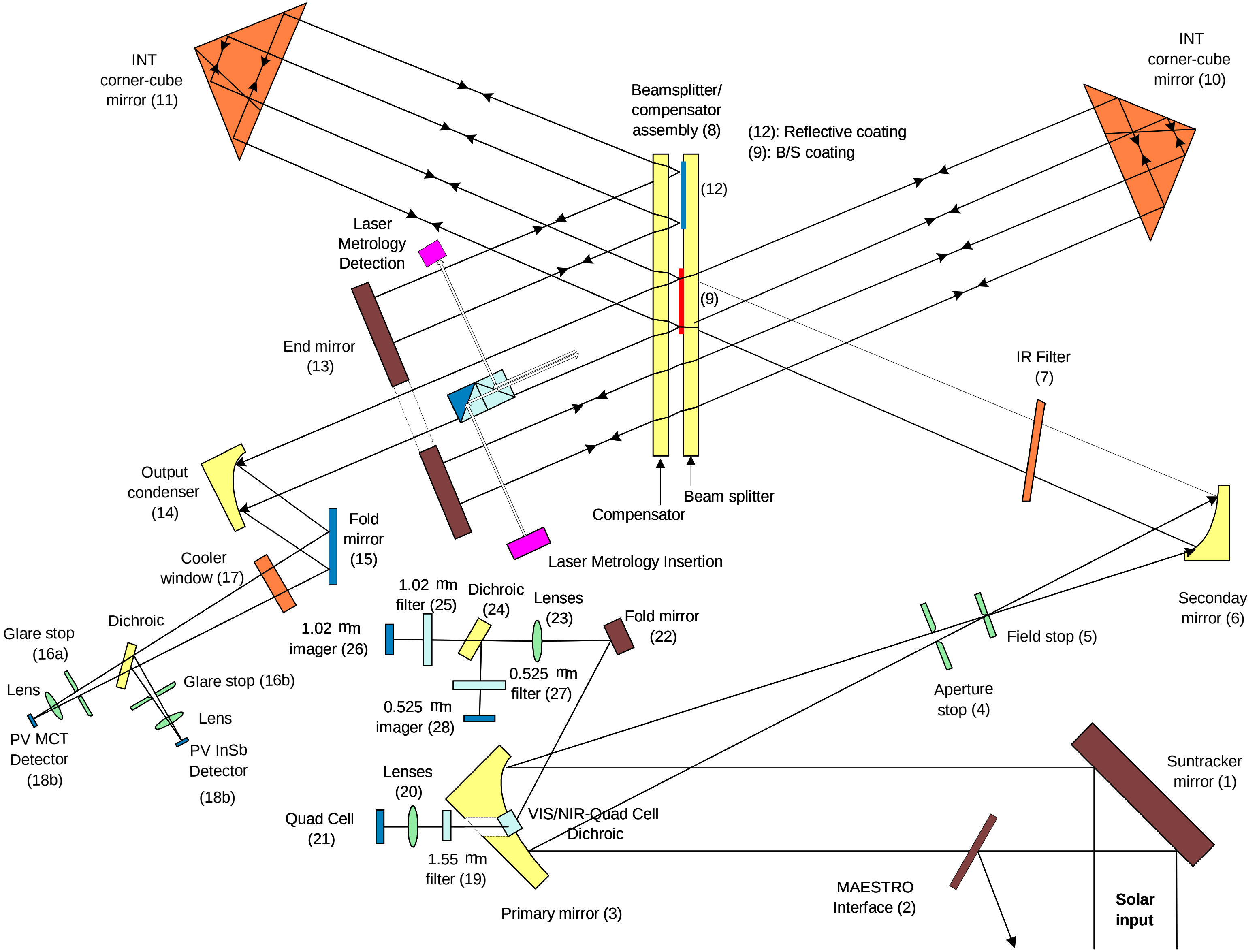




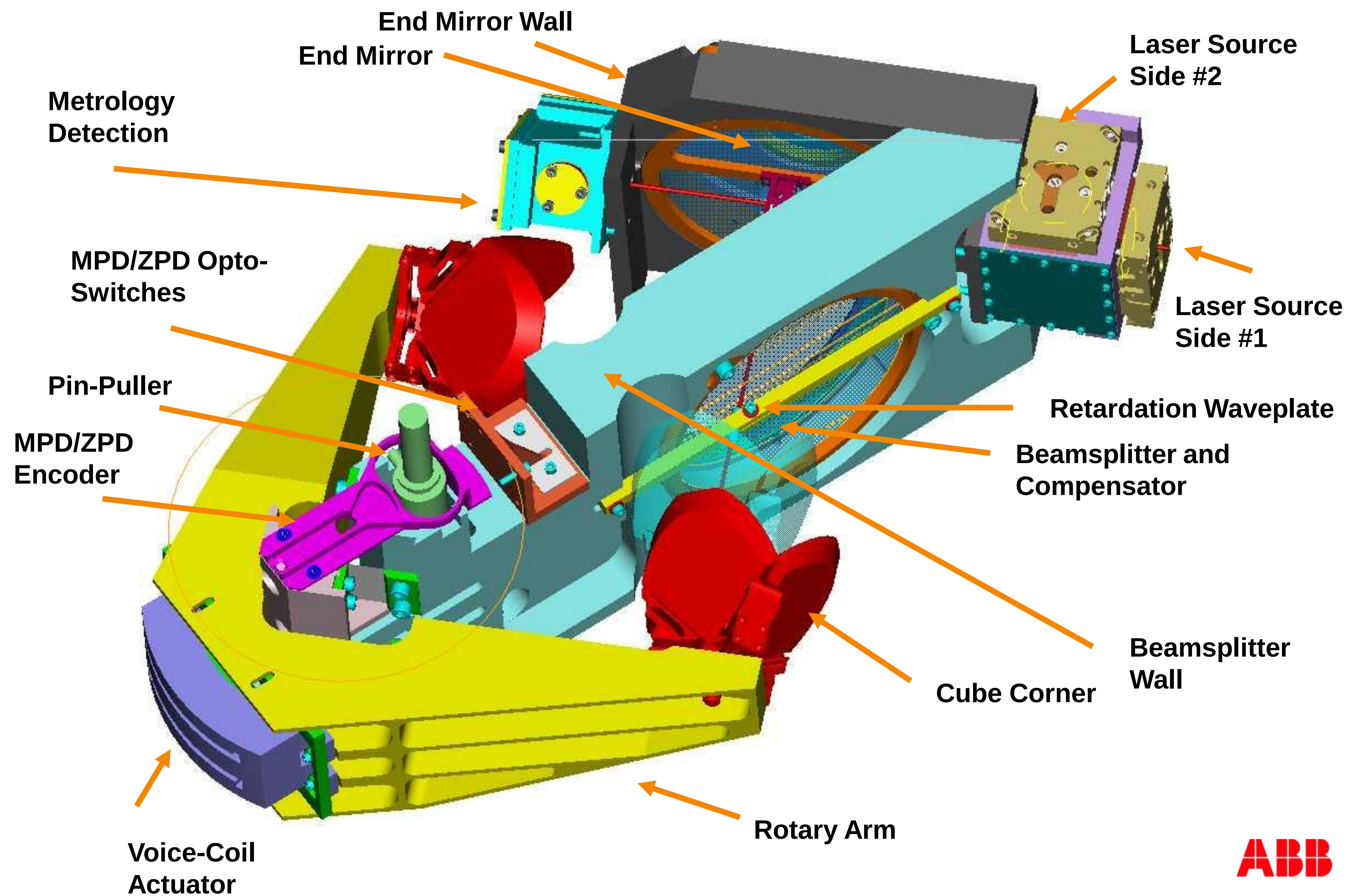
ACE-FTS Instrument Key Specifications

Operating Parameters	Nominal	Units	Comments
Spectral resolution	0.026	cm^{-1}	ILS FWHM
NESR	< 1	%	Of a 5800K blackbody
Transmittance accuracy	< 1	%	Absolute between 0-100%
Spectral range	750-4100	cm^{-1}	InSb & MCT (2 bands)
Instrument FOV	1.25	mrad	Circular
Interferometer divergence (full)	6.25	mrad	5x telescope
Interferometer aperture diameter	20	mm	Circular
Optical path difference	+/-25	cm	Optical units, double-sided
Sweep velocity	25	cm/s	Optical units (factor 8)
Measurement duration	2	sec	+ 75 msec turnaround
VIS/NIR imager bands	525, 1020	nm	Two distincts imagers
VIS/NIR SNR	> 2000		
Suntracker pointing knowledge	< 15	μrad	Allocated value
Suntracker pointing accuracy	< 500	μrad	Allocated value
Suntracker pointing stability	< 5	μrad	Allocated value
Weight	41.4	kg	Allocated value
Average power	37	W	Allocated value
Instrument lifetime	> 2	years	On-orbit

FTS design


INT
corner-cube
mirror (11)
Beamsplitter/
compensator
assembly (8)
(12): Reflective coating
(9): B/S coating
INT
corner-cube
mirror (10)
(12)
Laser
Metrology
Detection
(9)
End mirror
(13)
IR Filter
(7)
Output
condenser
(14)
Compensator
Beam splitter
Fold
mirror
(15)
Laser Metrology Insertion
Cooler
window (17)
1.02 mm
filter (25)
Dichroic
(24)
Lenses
(23)
Fold mirror
(22)
Seconday
mirror (6)
Glare stop
(16a)
Dichroic
1.02 mm
imager (26)
Field stop (5)
Lens
Glare stop (16b)
0.525 mm
filter (27)
Aperture
stop (4)
Lens
0.525 mm
imager (28)
PV MCT
Detector
(18b)
PV InSb
Detector
(18b)
Lenses
(20)
Suntracker
mirror (1)
Quad Cell
(21)
VIS/NIR-Quad Cell
Dichroic
1.55 mm
filter (19)
MAESTRO
Interface (2)
Solar
input
Primary mirror (3)

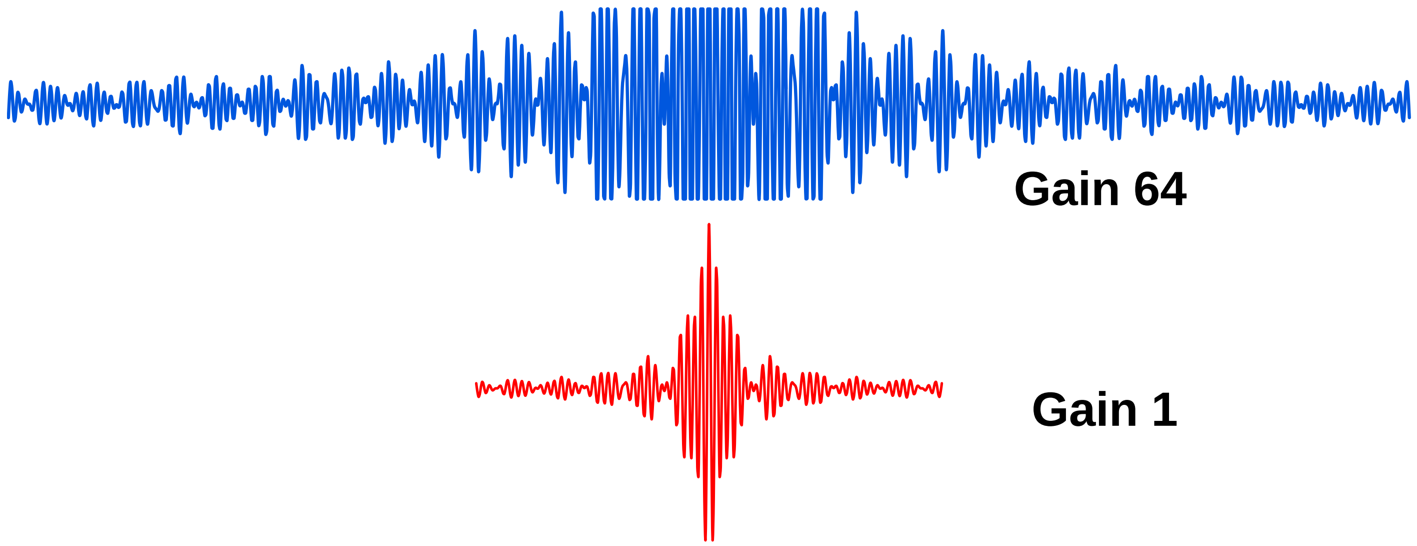
ACE-FTS Interferometer Sub-System



ABB

Limitation of fast ADCs for flight

- Fast ADCs available for flight have 12 bits
  - Each detector output is provided with 2 digitizing channels
    - High gain channel and low gain channel
    - Use low gain channel where high gain saturates
    - Adjust gain and offset in post processing
      - Provides effective 18 bit digitizing

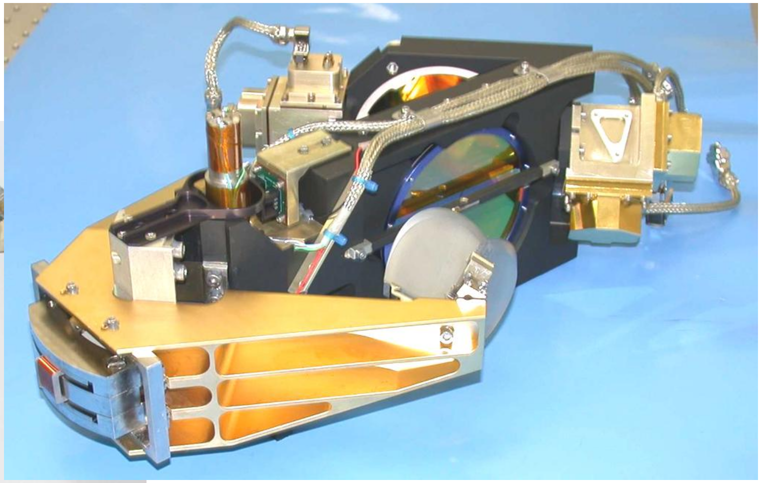


ACE FTS

- Scisat-1 launched in August 2003 on Pegasus launch vehicle
- Planned mission duration 2 years
- Continues to operate without any degradation of
- performance today

- Interferometer side

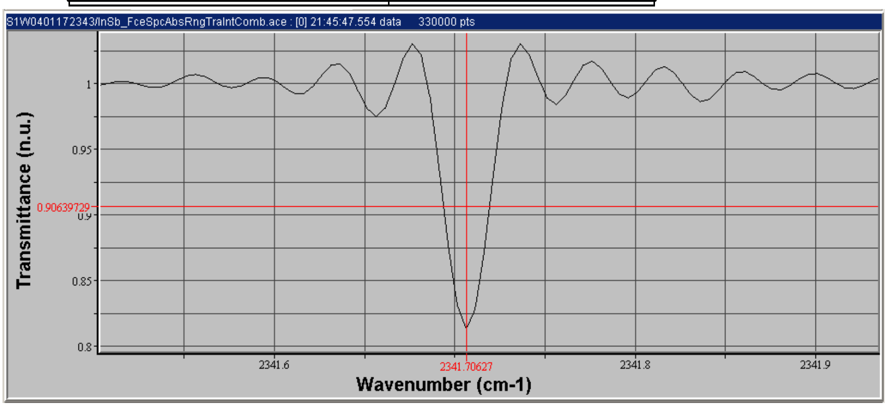
- Input optics side

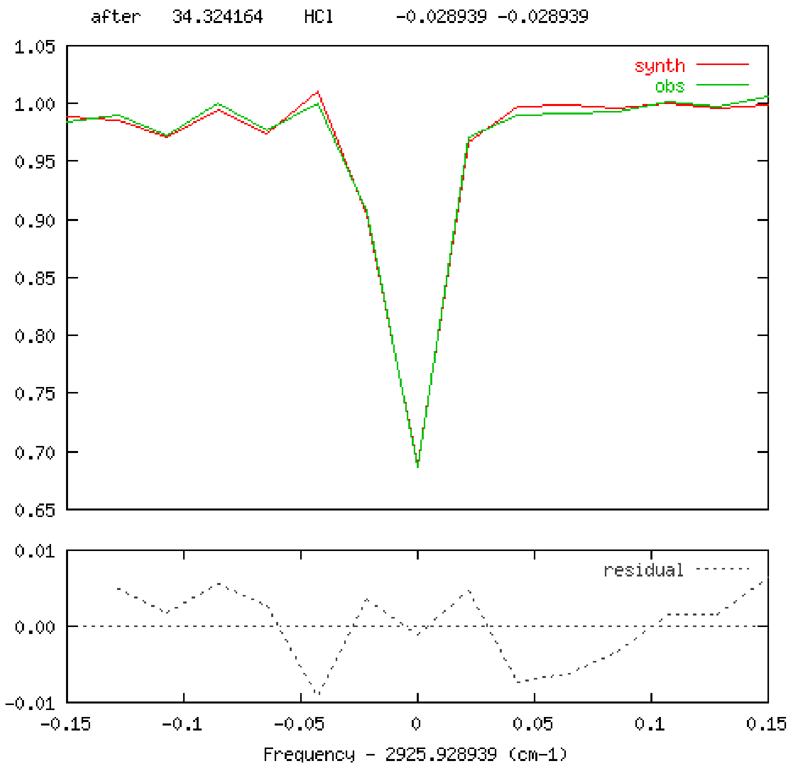


- Flight interferometer

On-orbit performance

Spectral Resolution (cm^{-1})	Spectral Frequency (cm^{-1})
0.0252	1032
0.0245	1576
0.0261	2364
0.0273	3722

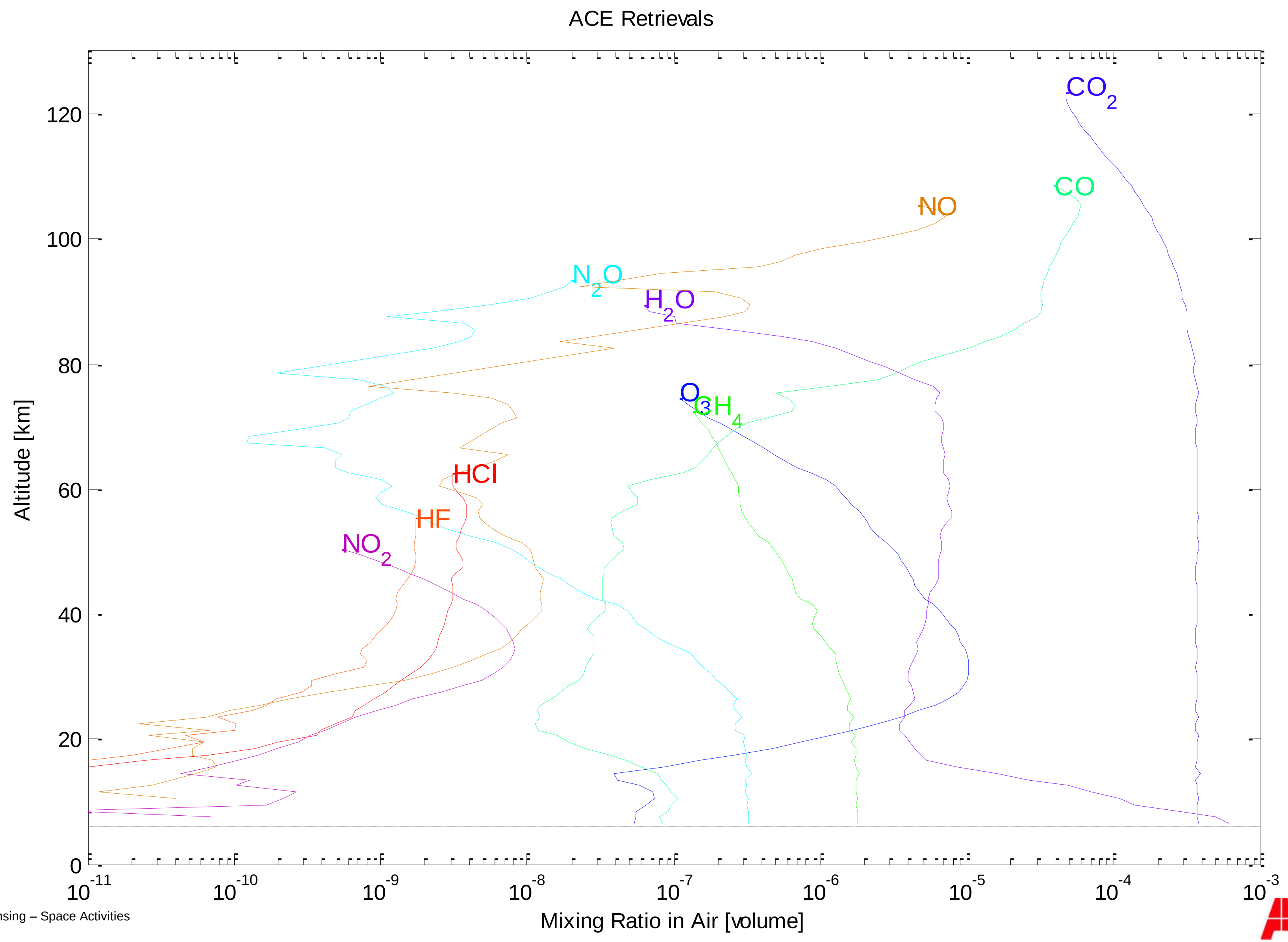




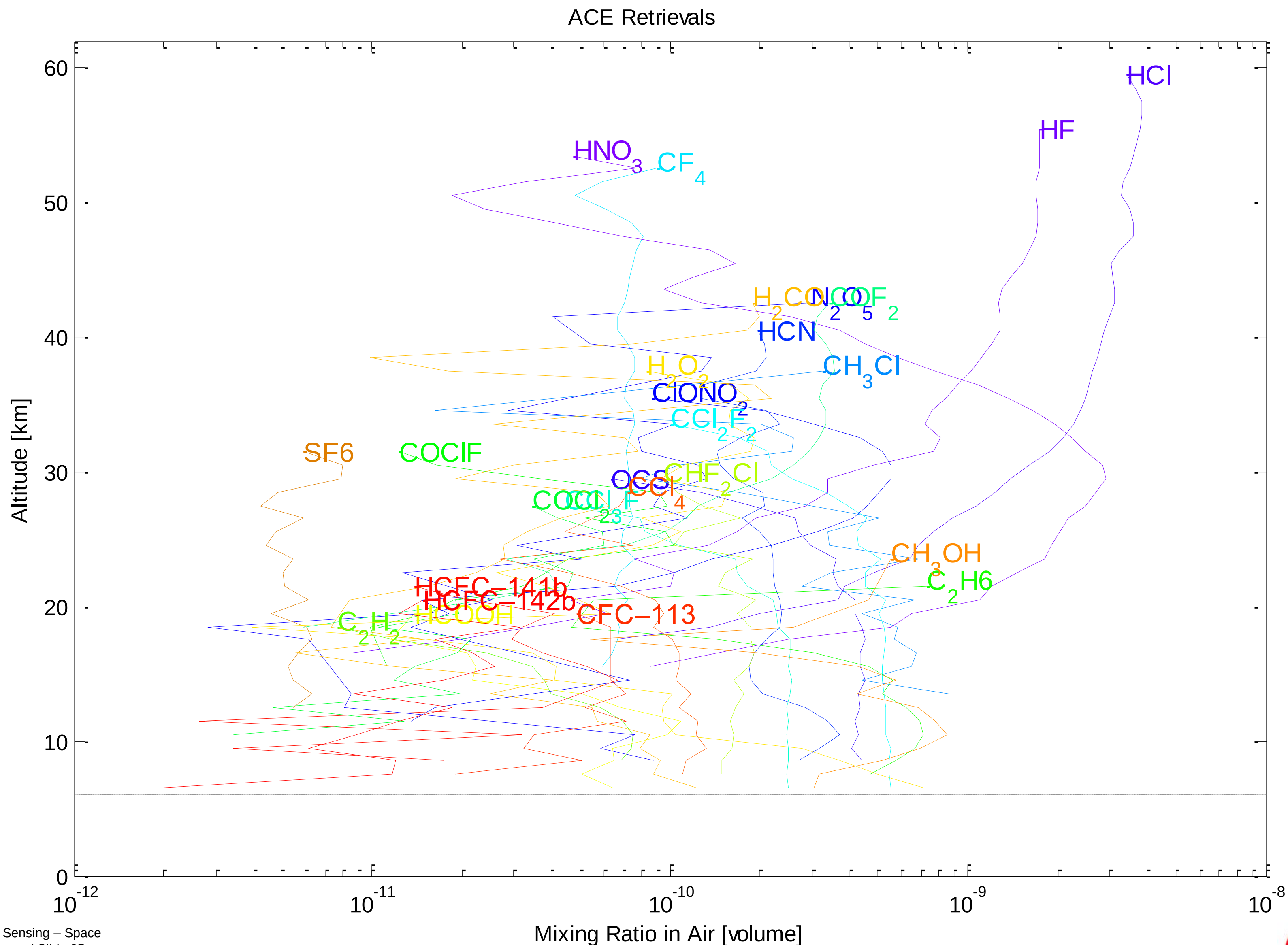
- Spectral resolution meets specification
- For OPD +/-25 cm expect FWHM 0.026cm-1 no apodization

- Fitting with theoretical sinc line shape
  - Leaves excess residue
    - Small deviation from theoretical shape
  - Can be modeled with FOV parameters or
  - Empirical line shape model

Measured profiles



Measured Profiles



ACE Summary

- ACE measures vertical distributions (profiles) of atmospheric molecular species
- ACE has accomplished its original mission
  - It has significantly contributed to our understanding of the chemistry affecting Ozone
- ACE has highest sensitivity for upper tropospheric and lower stratospheric (UTLS) molecular species
- ACE is an excellent probe for sub-ppb species in UTLS
- UTLS is atmospheric region of maximum greenhouse effect
  - Lower measurement limit is about 5 km for cloud free conditions
  - Useful for tracing biomass burning plumes
  - Useful for tracing pollutant plumes that enter the UTLS
- ACE provides an inventory of greenhouse gases in the UTLS
- To date more than 230 papers have been published related to ACE data

ACE related activity

- The ACE interferometer is very robust and reliable
  - Several copies have been produced for ground based solar spectroscopy
    - U of T PARIS instrument
    - Chinese Beijing instrument
- A copy of the ACE interferometer was produced for the JPL MATMOS project
  - Planned mission to orbit Mars
  - Measure Martian atmosphere by solar occultation
    - Mission was cancelled by NASA
- SciSat follow on missions are being contemplated
  - With faster scanning and narrower field of view
    - To improve vertical resolution
  - At reduced spectral resolution to reduce cost

Greenhouse Gas Measurement in Japan

- Bomem has a long relationship with NEC-Toshiba space systems and the Japanese space agency (JAXA)
- A small interferometer called Solar Occultation For Inclined-orbit Satellite (SOFIS) was designed and built around 2000.
  - The mission for this interferometer did not materialize and the interferometer was not used.
- Later ABB Bomem was requested to study the use of a FTS for the monitoring of greenhouse gases from space.
  - Particularly carbon dioxide (CO_2) and Methane (CH_4).
  - Use sunlight reflected from the ground by means of a nadir viewing satellite instrument.
- Work on the GOSAT mission was started ~2004

Preparatory work for GOSAT

- Design and build FTS for ground based reflected solar spectroscopy
  - Named Tokyo system
  - To validate measurement feasibility
- Design and build a second unit for airborne reflected solar spectroscopy
  - Measurement campaigns over different terrains for further validation
  - Named Tsukuba system
- The required specifications were established
- Require an interferometer with extremely wide spectral range from the LWIR to the visible
- Require high transmission efficiency to maximize SNR
- Require 0.2 cm^{-1} resolution to resolve rotational structure of CO_2 bands

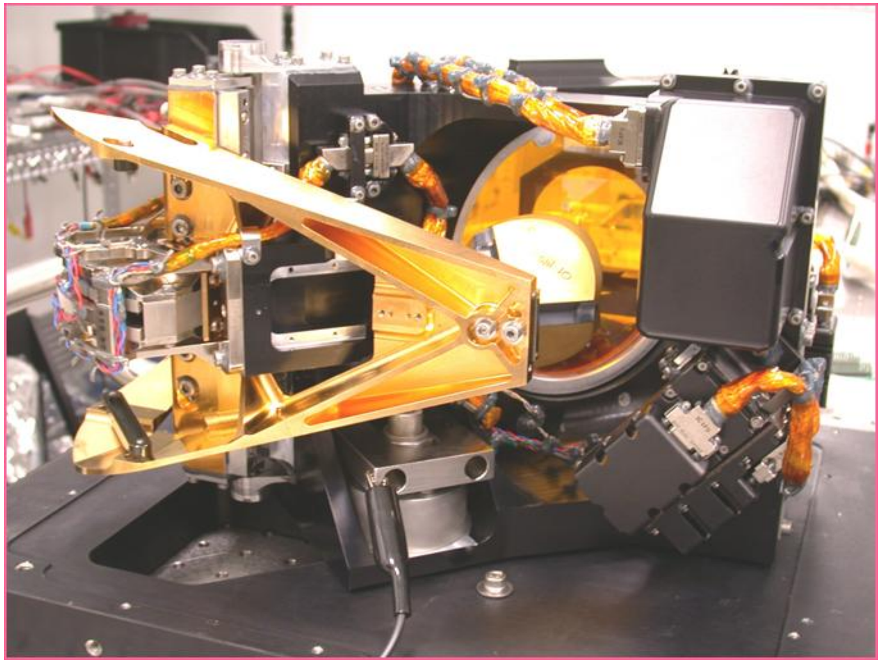
Specifications for GOSAT TANZO-FTS

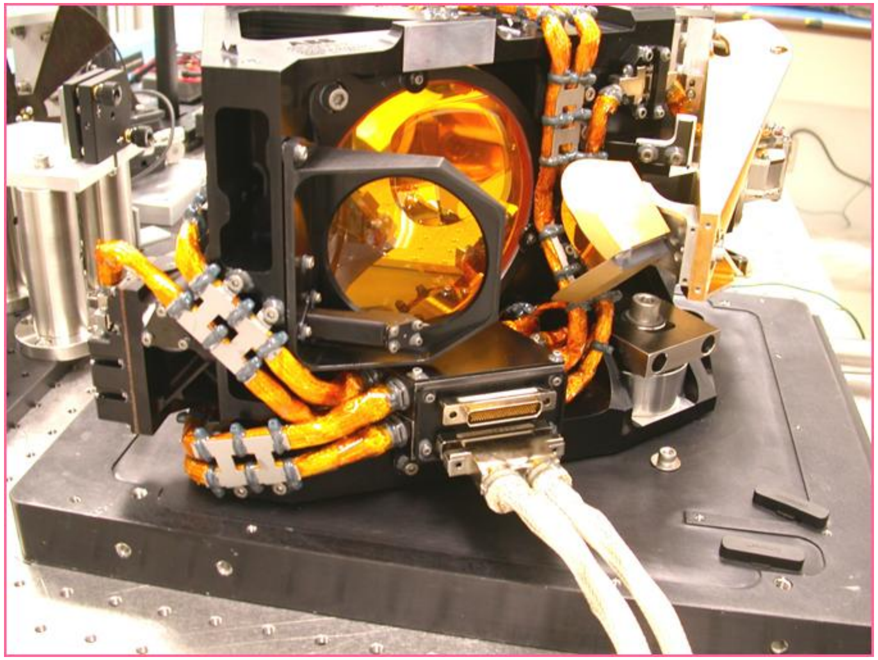
ポインティング機構部	構　成	2軸走査鏡（完全冗長）			
	走査角	クロストラック（±35 deg） Cross track scan アロングトラック（±20 deg） Along track scan			
	視　野	瞬時視野 10.5 km　走査幅 790 km Orbit altitude, GFOV			
フーリエ干渉計	速　度	1.1, 2, 4 秒／（インターフェログラム） scan times			
	バンド	1P, 1S	2P, 2S	3P, 3S	4
	波長範囲	0.75 μm - 0.78 μm	1.56 μm - 1.72 μm	1.92 μm - 2.08 μm	5.5 μm - Spectral ranges 14.3 μm
	分　光 分解能(cm^{-1})	0.5	0.2	0.2	0.2 Resolution
	信号対 雑音比 （SNR）	>300	>300	>300	>300
	検出器	Si	InGaAs	InGaAs	PC-MCT
	校　正	（感度）　太陽照度、深宇宙、月 （装置関数）　1.55 μmレーザ			Metrology wavelength 黒体、深宇宙

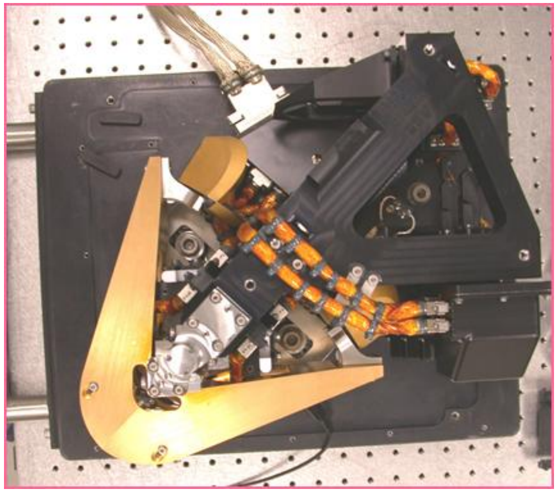
GOSAT Characteristics

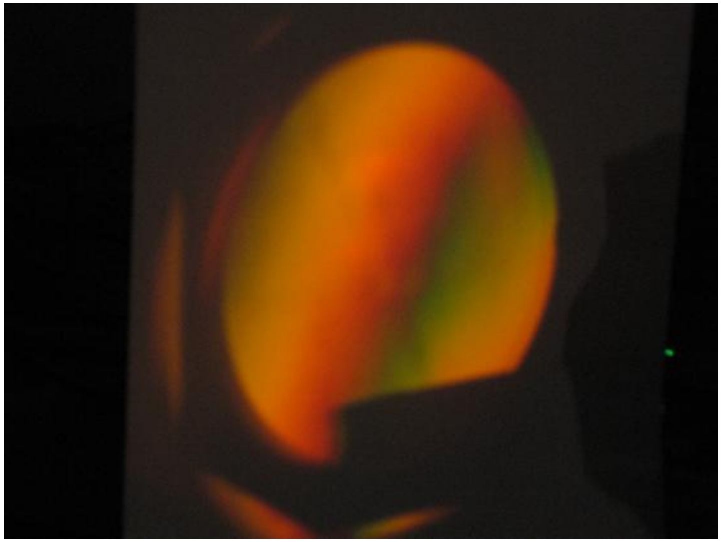
- Design based on M100 technology
  - Scale up beam diameter to 68 mm
  - Scale up resolution from 1 cm^{-1} to 0.2 cm^{-1}
    - Scan distance is +/-2.5 cm OPD
  - Proprietary beamsplitter with high efficiency from 700 to 14000 cm^{-1}
  - Flat polarization response
    - Desire to measure s and p separately
  - With long scan stroke, flex blades need to be thin to avoid high stress
    - Could break during launch
      - Develop a “passive caging” of double pendulum scan arm
      - Constrain lateral displacement of scan arm without touching
  - Require precise scan timing to be able to measure same ground FOV with an orbit that precisely repeats coverage every 3 days

GOSAT Design



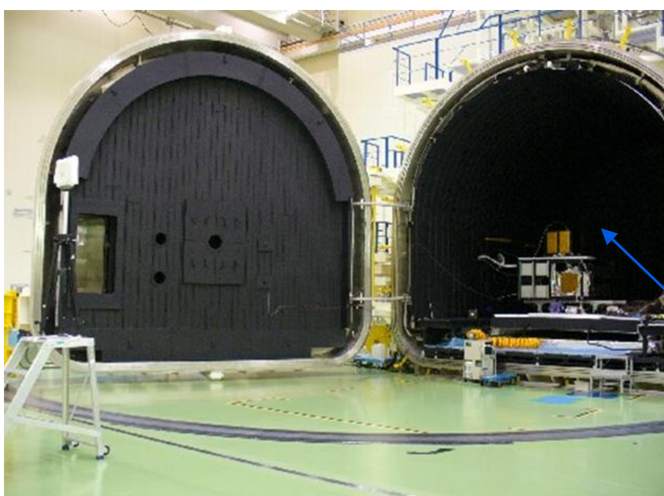






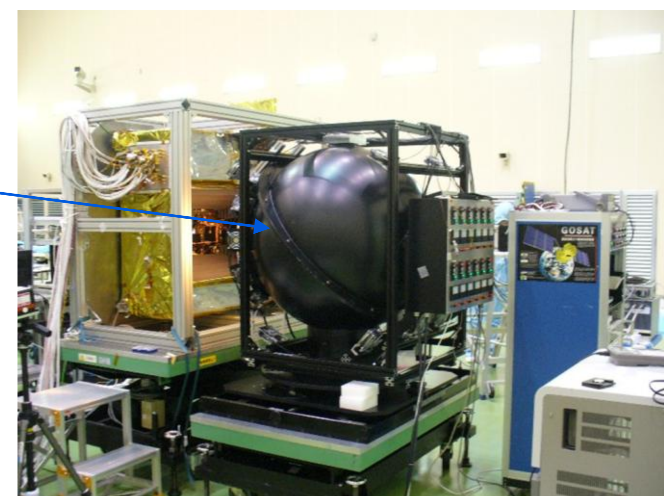
GOSAT Preflight Testing

- GOSAT system passes all performance specs
- Concern about micro-vibrations in space
  - There is no damping
    - Add interferogram sampling timing to minimize effects of vibrations



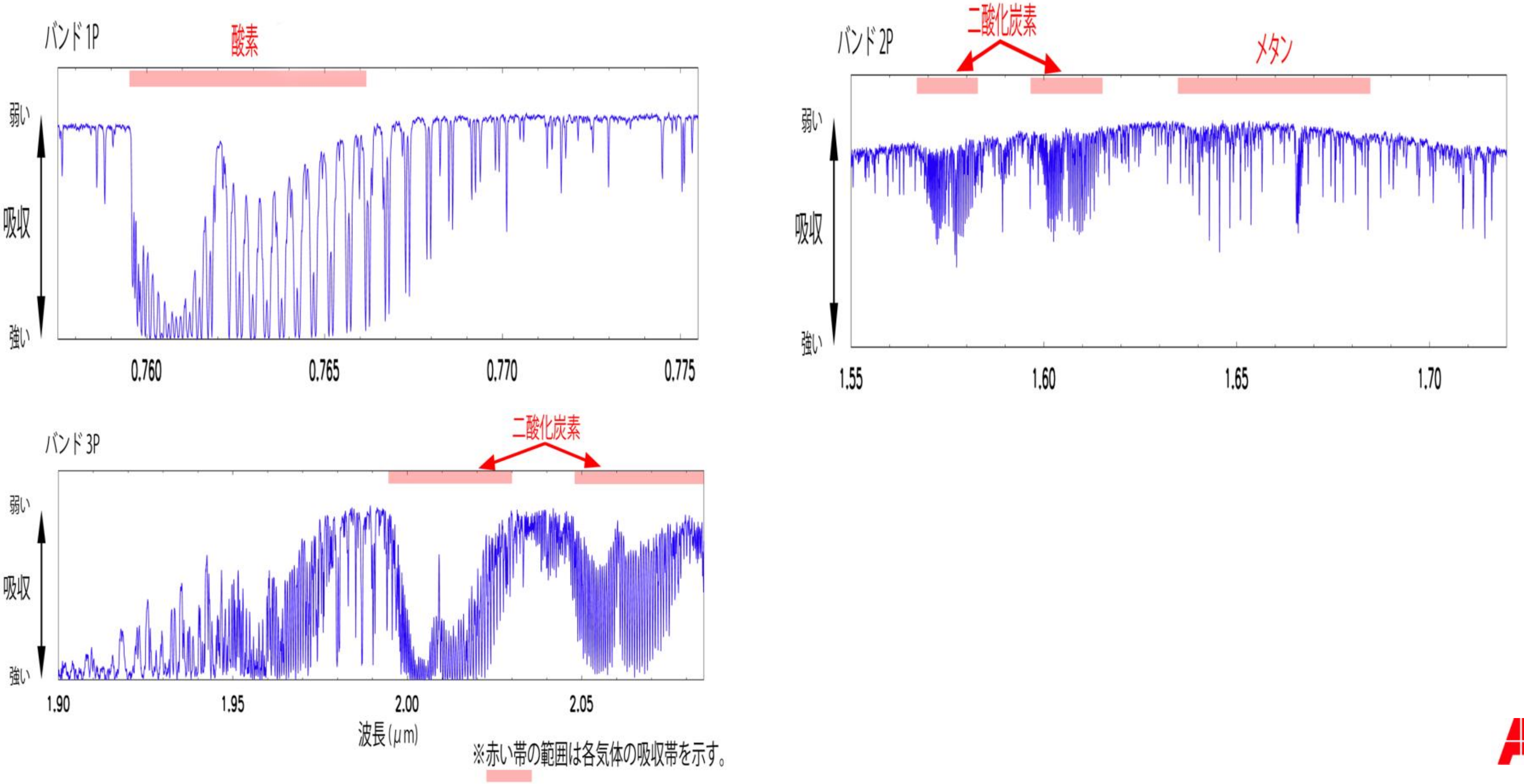
6 m diameter thermal vacuum chamber

Reflected solar light simulator



GOSAT

- GOSAT was launched January 2009
    - Expected mission duration 5 years
- Data looks very good at first light



GOSAT Seven Years in Orbit

- The retrieval of mixing ratios of CO2 and CH4 is challenging
  - Least squares fitting with laboratory reference spectra
    - That include temperature and pressure distribution of atmosphere
- Requires accurate knowledge of instrument response
  - Discovered several small deviations from assumed response
    - Non linearity in some electronics components
  - Much work done to model small anomalies and correct the data
- Recently issued 10^{th} version of processing software for determination of radiance spectra from raw data provides very consistent results for entire 7 year data set.
  - Determination of aerosol in atmosphere is biggest uncertainty in mixing ratio retrievals
- Discovery of fluorescence emission from tropical forests causes bias in oxygen retrieval
  - Fluorescence correction is included in retrieval
  - Fluorescence signal is useful for satellite monitoring of health of biosphere

GOSAT Seven Years in Orbit

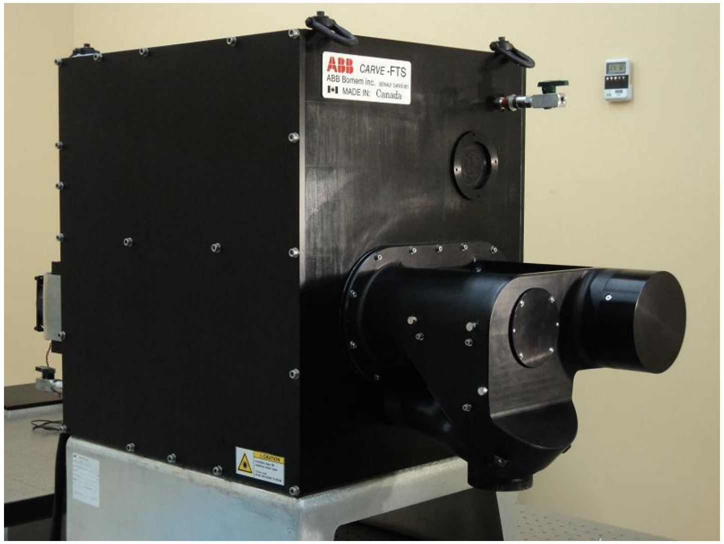
- During the mission several instrument problems have occurred as well
  - The laser injection mirror into the interferometer is slowly changing angle
  - Diminishes the detected fringe signal.
    - Fringe signal has reduced by factor 3 in seven years
      - SNR was very high at start of mission
      - Still enough margin for excellent operation
    - Reduced fringe signal and pointing mirror vibrations has caused fringe mis-counts at turnaround
      - Causes ZPD shifts in the recorded interferogram
      - Requires repositioning commands
  - The pointing mirror has shown positioning errors and excessive vibrations when moving
    - Recently switched to redundant second mirror
  - One of two solar panels has stopped pointing at the sun
    - There is sufficient power to continue the mission

GOSAT Seven Years in Orbit

- The JPL OCO-I satellite was launched only several days after the GOSAT launch
  - It failed to reach orbit
- The JPL team and as many as 9 other science teams around the world have worked extensively on the retrieval of GOSAT data
  - With the latest radiance processing software, the retrieval accuracy for column averaged dry air mole fractions is ~0.5% for CO_2 (or 2 ppm) and 0.7% for CH_4 (or 13ppb)
    - Exceeds initial specification by 2x
  - Has been maintained consistently over the 7 years on orbit
- With JPL OCO-II in orbit since July 2014, GOSAT has concentrated on an “agile pointing” mode whereby during each orbit the satellite will point to many specific target areas such as mega cities and oil exploration areas

JPL Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) project

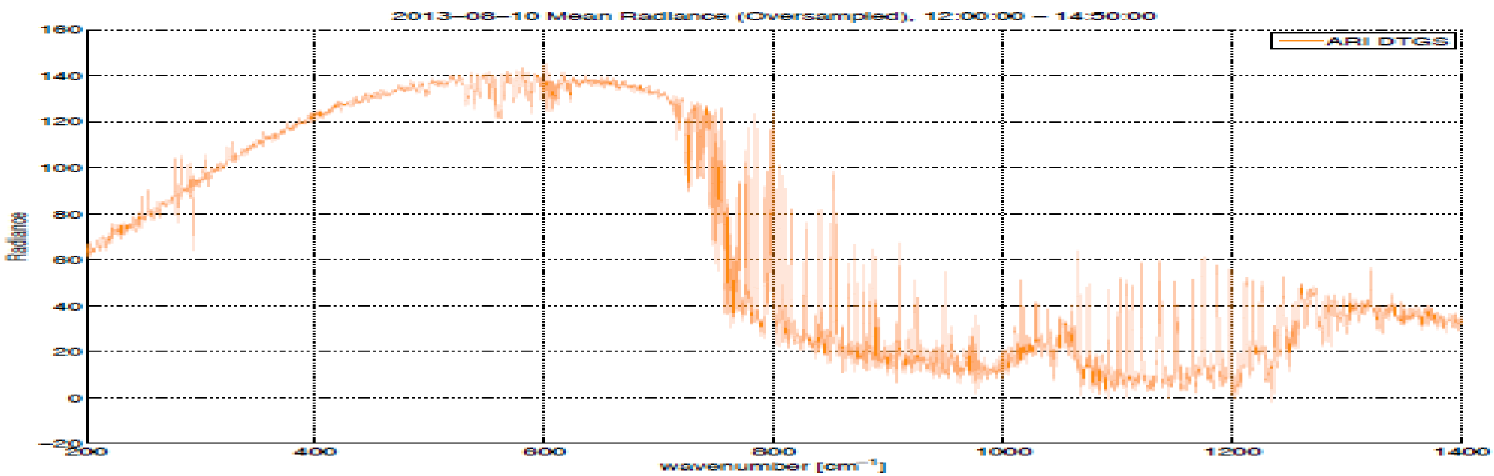
- A copy of the GOSAT FTS has been produced for JPL
  - For operation in a small aircraft
  - Principally to measure CO2, CH4 and CO column densities over Alaska
  - Smaller viewing footprint than GOSAT
    - Aircraft altitude



ABB

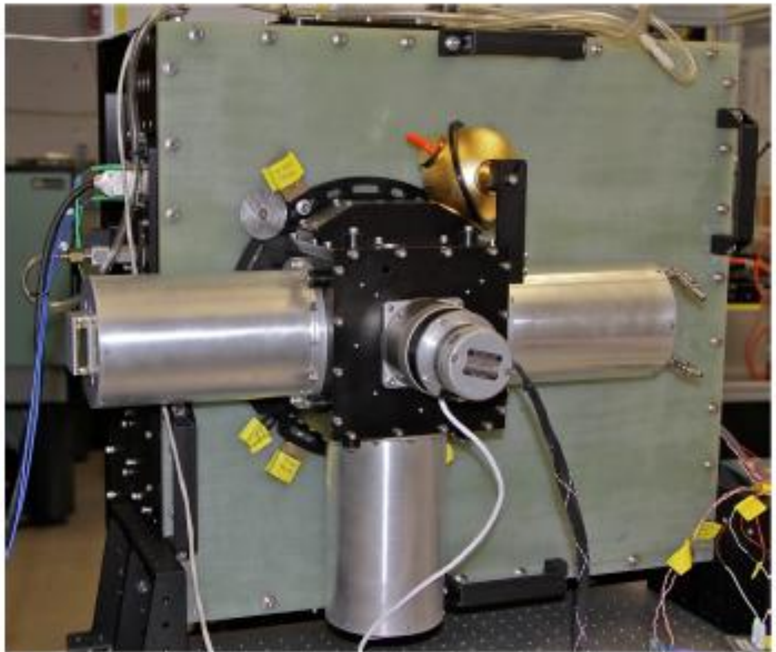
The CLARREO mission

- Establish highly accurate global bench-mark measurements from satellite that detect and characterize climate change over decadal time scales
  - Determine annual regional changes on scales of order 15ºx30º latitude/longitude
  - Determine seasonal changes (bi-monthly) on larger scales of order 50ºx50º



The CLARREO mission

- Emphasis on absolute NIST traceable Radiometric calibration
  - Multiple blackbody sources with melt point temperature sensors
  - Emissivity monitoring
  - Very high radiometric precision (sensitivity and stability)
- Expected to measure climate change temperature effect within 10years



Concluding remarks

- Bomem which is now part of ABB has been successful in advancing the state of the art of FTS
  - In the mid sixties the technique was new and interferometers were fragile
    - Data processing capability was very limited
  - In the mid eighties commercial FTS flourished and displaced dispersive IR spectrometers completely
- Bomem was not the biggest commercial vendor of FTS but ranked in the top 4
  - It developed a niche for reliable simple FTS much appreciated by industrial QA labs and for process monitoring
- In the nineties Bomem realized that the M series was extremely stable and reliable and provided very accurate reproducible spectra
  - These were attributes suitable for long unattended operation such as in satellites
- The three satellite projects completed to date have been very successful

Societal Benefits

- Improved weather prediction
  - Cost saving of extending reliable weather prediction by 1 day is staggering
    - Logistics in transportation
    - Agriculture impact
    - Saving lives
- Hurricane Sandy
  - With Help from Cris sensor and Eurpean IASI 72 hour prediction of path was accurate to within unprecedented +/-20 km
    - Evacuation measures saved many lives
- Contribution of ACE to understanding of ozone chemistry and also climate change
  - Has made the Montreal Protocol a success, ozone is increasing
  - Has contributed to a significant reduction of climate change deniers at Paris climate conference
- Gosat and OCO are crucial in monitoring compliance to greenhouse gas reductions

Power and productivity
for a better world™