SABER Experiment Performance Review

Presented by
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TIMED SWG Meeting
Johns Hopkins University Applied Physics Laboratory
March 15, 2004
# SABER Science Team

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<tr>
<th>Co-Investigators</th>
<th>Institutions</th>
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<tr>
<td>James M. Russell III</td>
<td>Hampton University</td>
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<tr>
<td>Martin G. Mlynczak</td>
<td>NASA LaRC</td>
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<td>Ellis E. Remsberg</td>
<td>NASA LaRC</td>
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<td>Doran J. Baker</td>
<td>SDL, USU</td>
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<td>BAS, Cambridge</td>
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<td>Larry L. Gordley</td>
<td>GATS, Inc.</td>
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<td>Manuel Lopez-Puertas</td>
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<td>Richard H. Picard</td>
<td>AFRL</td>
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<tr>
<td>Christopher J. Mertens</td>
<td>NASA LaRC</td>
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</table>
SABER Science Goal

To provide new data and improved understanding of the structure, energetics, chemistry and dynamics of the TIMED core region extending from 60 km to 180 km.
SABER Scientific Objectives

- Study the M/LT thermal structure and its variations
- Implement studies of energetics and radiatively active species in the non-LTE environment
- Analyze Oy and HOy chemistry
- Conduct dynamics studies
SABER Measurement Objectives

- Conduct global-scale, simultaneous, vertical profile measurements of temperature, key chemical constituents, and key emission features, including the following:
  - Kinetic Temperature
  - $O_3$, $H_2O$, $NO$, $CO_2$
  - $O_2(1\Delta)$, $OH(\nu)$, $NO(\nu)$, $O_3(\nu3)$, $CO_2(\nu2)$
  - Atomic species $O$ and $H$ ($O$ inferred 4 different ways)

- Conduct measurements (e.g., $T$, $O_3$, $H_2O$, $CO_2$) that can be used to derive and study dynamical quantities such as geopotential height and potential vorticity

- Conduct measurements of $O_3$, $H_2O$, $OH(\nu)$, $O$, and $H$ to study ozone and odd hydrogen photochemistry in this region
Conduct measurements of key radiative emissions to study energetics in the TIMED core region

- True cooling: \( \text{CO}_2(\nu 2), \text{NO}(\nu), \text{O}_3(\nu 3), \text{H}_2\text{O}(\nu 2) \)
- Solar heating: \( \text{O}_3, \text{O}_2, \text{CO}_2(\nu 3) \)
- Chemical heating: \( \text{O}_3, \text{O}_2, \text{OH}(\nu) \)
- Reduction of solar and chemical heating efficiencies: \( \text{O}_2(1\Delta), \text{OH}(\nu), \text{O}_3(\nu 3), \text{CO}_2(\nu 3) \)
SABER TIMED Science Contributions

- Measures T and $\rho$ in the TIMED core region globally

- Observes key constituents in the lower portion of the core region globally including $\text{O}_3$, $\text{H}_2\text{O}$, $[\text{O}]$, $[\text{H}]$ and $\text{CO}_2$

- Measures tracer molecules $\text{CO}_2$ and $\text{H}_2\text{O}$ for dynamics studies

- Measurements made day and night with high vertical resolution (2.2 km IFOV) independently of spacecraft attitude and attitude rate information

- Main radiative emission features for energetics are measured: true cooling, chemical heating, solar heating and key emissions that reduce solar and chemical heating efficiency

- Observations cover altitude range from the GW source region in the stratosphere, to altitudes where GWs break (~100 km), and in the lower thermosphere
SABER Experiment Approach
LIMB EMISSION EXPERIMENT VIEWING GEOMETRY AND INVERSION APPROACH

\[
N(Ho) \cong \int \int J_\nu(x) \frac{d\tau(\nu,q,T,P)}{dx} dx \, d\nu
\]

TANGENT POINT Ho

RAY PATH TO SATELLITE

\{ Ho

N(Ho) \cong \int \int J_\nu(x) \frac{d\tau(\nu,q,T,P)}{dx} dx \, d\nu

q known (e.g. CO\textsubscript{2}) \Rightarrow J_\nu \Rightarrow T

J_\nu \text{ known} \Rightarrow q \text{ (e.g. O}_3, \text{ H}_2\text{O, CO}_2\ldots\)
SABER Focal Plane Channel Locations

# 4  O₃ 9.3 μm

# 5 H₂O 6.8 μm

# 1 CO₂- N 15.2 μm

# 3 CO₂- W 15.0 μm

# 8 OH(A) 2.07 μm

# 6 NO 5.3 μm

# 2 CO₂- W 15.0 μm

# 7 CO₂ 4.26 μm

# 9 OH(B) 1.64 μm

# 10 O₂(^1Δ) 1.28 μm

2 km @ 60 km

1.49°
SABER Daytime Radiance Versus Altitude for 55°S, 287°E, January 8, 2002
SABER Measurement and Inflight Calibration Cadence

- Downscan or upscan every ~53 seconds
  - ~450 km to ~ –20 km tangent height in ~3.5° latitude

- Spacelook Counts updated every ~ 3.5 Minutes

- Responsivity updated every ~ 8 Minutes by viewing a hot In-Flight Calibration (IFC) Blackbody
SABER In-flight Calibration System Updates
Spacelook Counts Every ~ 3.5 Minutes

- Acquisition scan finds the limb
- Adaptive scan tracks the limb

Calibration Scan (BB) 12secs
Adaptive Scan 107 secs
Gain Cycle Spacelook 11secs
Baffle Scan 7secs

Ground
Space
SABER In-flight Calibration System
Updates Responsivity Every ~ 8 Minutes

Calibration Scan (BB)
Calibration Scan (JS1)
Calibration Scan (JS2)
Calibration Scan (JS3)

IFC to Calibration 7mins 52secs
TIMED spacecraft being prepared for acoustic tests at the NASA Goddard Space Flight Center
SABER Daily Latitude versus Longitude Coverage (83°N - 52°S)

Longitude (degrees)

Latitude (degrees)

North viewing phase of the TIMED yaw cycle
SABER Level 2A Routine Data Products

- Vertical profiles of the following parameters day and night:
  - Kinetic T, P, density
    - 10 - 105 km
  - O$_3$ mixing ratio (9.6$\mu$m)
    - 15 - 100 km
  - O$_3$ mixing ratio (1.27$\mu$m)*
    - 50 - 95 km
  - H$_2$O mixing ratio
    - 15 - 80 km
  - CO$_2$ $\rho$ (4.3$\mu$m and 15 $\mu$m)
    - 85 - 150 km
  - NO 5.3$\mu$m VER**
    - 100 - 180 km
  - OH 1.6$\mu$m VER**
    - 80 - 100 km
  - OH 2.0$\mu$m VER**
    - 80 - 100 km
  - O$_2$(1$\Delta$) 1.27$\mu$m VER**
    - 50 - 105 km

* Day only
** Volume Emission Rate
NLTE SABER and HALOE Temperature

HALOE vs. SABER T. (May-July 2002 - Nighthime) - SH mid lat.
- Temperature and Constituent densities
  - Kinetic T, P, density $Z \geq 105\ km$ night and day
  - [O] concentration
    - O$_3$ day / night $\Delta$’s $60 - 80\ km$ day
    - O$_2$(1$\Delta$) nightglow $80 - 100\ km$ night
    - O$_3$(9.6$\mu$m) / OH(2.0$\mu$m) $80 - 100\ km$ night
    - CO$_2$(4.3$\mu$m) / CO$_2$(15$\mu$m) $100 - 135\ km$ day
  - [H] Concentration $80 - 100\ km$ night and day

- Cooling Rates
  - CO$_2$(15$\mu$m) $20 - 140\ km$
  - NO (5.3$\mu$m) $100 - 180km$
  - O$_3$ (9.6$\mu$m) $20 - 100\ km$
  - H$_2$O (6.7$\mu$m and far IR) $20 - 70\ km$
SABER Level 2A Analysis Data Products

- Solar heating rates, including airglow losses (20 - 100 km)
  - O$_3$ (Hartley, Huggins, Chappius, and other uv bands)
  - O$_2$ (Schumann-Runge, Ly-$\alpha$, Herzberg, and Atmos. Bands)
  - CO$_2$ (4.3 $\mu$m)

- Chemical heating rates (80 - 100 km)
  - O$_x$ and HO$_x$ families

- Airglow/Chemiluminescent, Emission/Heating Efficiency
  - O$_2$(^1$\Delta$) 50 - 105 km
  - OH(1.6 $\mu$m) 80 - 100 km
  - OH(2.0 $\mu$m) 80 - 100 km

- Geostrophic Wind 20 - 100 km
Comparison of SABER NO 5.3 μm Energy Loss Rates for April, 2002 and October, 2003 solar storms

October 30, 2003 82º N

April 20, 2002 82º S

Peak energy loss rates are comparable for the two storms
SABER Level 3 Data Products

- Zonal mean pressure versus latitude cross sections
  - Orbit, daily, weekly, monthly and seasonally averaged

- Polar stereographic and Lambert projection maps on constant pressure and isentropic surfaces
  - Orbit, daily, weekly, monthly and seasonally averaged maps
LTE Temperature Zonal Mean and global plot on July 9, 2002
SABER Instrument Performance and Measurement Requirements
SABER Instrument In-Orbit Performance Is Excellent

- Experiment Status
  - SABER instrument is performing in orbit as designed
  - FPA temperatures are being held steady at ~ 74K by the cooler
  - Cooler performance excellent and stable
  - Scan system is performing well
  - Noise performance is excellent
  - Data collection is routine

- No instrument anomalies

75 kg, 77 watts, 77 x 104 x 63 cm, 4 kbs
SABER Instrument Refrigerator Cold
Link Efficiency Trend

Graph showing the trend of Delta T1-5 (Deg K) from August to November 2003, with an average line.
SABER Instrument Refrigerator
Compressor Stroke Time Trend

RCS - [Counts]

Aug 2003
Sep 20030718 to 20031101
Oct
Nov

2003

Average
Scan mirror changes usually affect < ~ 100 scans per day and cause no data loss. No time trend evident.
SABER Noise Performance In-Orbit is Stable

<table>
<thead>
<tr>
<th>Channel</th>
<th>Parameter</th>
<th>Jan 8, 2002*</th>
<th>April 25, 2002*</th>
<th>Jan 24, 2004*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO2 N</td>
<td>2.6</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>2</td>
<td>CO2 W</td>
<td>2.7</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>CO2 W</td>
<td>2.6</td>
<td>2.6</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>O3</td>
<td>3.0</td>
<td>2.6</td>
<td>3.4</td>
</tr>
<tr>
<td>5</td>
<td>H2O</td>
<td>3.2</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>NO</td>
<td>3.0</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>7</td>
<td>CO2 (4.3 µm)</td>
<td>1.6</td>
<td>1.7</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>OH(A)</td>
<td>2.0</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>9</td>
<td>OH(B)</td>
<td>2.3</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>10</td>
<td>O2(1Δ)</td>
<td>2.0</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

* RMS Counts

Gains set to noise = 3 counts.
All channels met or exceeded specifications.
In-orbit performance slightly better than laboratory.
SABER temperature and constituent accuracies inferred from correlative data comparisons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Altitude Range (km)</th>
<th>Estimated Accuracy</th>
<th>Mean Diff. With Correlative Data</th>
<th>Correlative Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>10 – 100</td>
<td>1.5 K, 15 - 80 km 4.0 K, 80 - 100 km</td>
<td>2 - 3 K</td>
<td>Lidar, NCEP, GPS, HALOE</td>
</tr>
<tr>
<td>$O_3$ (9.6 µm)</td>
<td>15 – 100</td>
<td>20%, 15 - 90 km 30%, 90 - 100 km</td>
<td>30%</td>
<td>Lidar, HALOE</td>
</tr>
<tr>
<td>$O_3$ (1.27 µm)</td>
<td>50 – 95</td>
<td>20%, 50 - 95 km</td>
<td>30%</td>
<td>HALOE</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>15 – 80</td>
<td>20%, 15 – 70 km 30%, 70 – 80 km</td>
<td>30%</td>
<td>HALOE</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>85 – 150</td>
<td>30%, 95 – 140 km</td>
<td>??%</td>
<td>TIME-GCM*, CWAS rocket</td>
</tr>
</tbody>
</table>

* Qualitative comparison only
SABER LTE Temperature Compared With Lidar at Mauna Loa on April 19, 2002

Coincidence
0.4 hour
1° latitude
2° longitude
SABER and UKMO temperatures at 10 mb (~30 km) show close agreement.
SABER V1.04 mapped geopotential height and derived geostrophic winds at ~65 km

Geopotential Height

February 5, 2002

Geostrophic Winds

February 12, 2002
### SABER Energetics (Energy Loss Rate) Accuracies
Based on Laboratory and In-Flight Calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Range</th>
<th>Estimated Accuracy</th>
<th>Observed Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current</td>
<td>(Potential)</td>
</tr>
<tr>
<td>OH(ν), 1.06 µm</td>
<td>80 – 100 km</td>
<td>3%, 80 - 90 km 10%, 90 - 100 km</td>
<td>10% (3%) (20%)</td>
</tr>
<tr>
<td>OH(ν), 2.10 µm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂(1Δ)*</td>
<td>50 – 105 km</td>
<td>3%, 50 - 90 km</td>
<td>10% (3%)</td>
</tr>
<tr>
<td>O₃ (9.6 µm) (Night)</td>
<td>15 – 100 km</td>
<td>3%, 50 - 90 km</td>
<td>3-7%</td>
</tr>
<tr>
<td>CO₂ (15µm)</td>
<td>15 – 120 km</td>
<td>3%, 90 – 120 km</td>
<td>3-7% 90-100km</td>
</tr>
<tr>
<td>CO₂ (4.3µm) (Day)</td>
<td>85 – 150 km</td>
<td>3%, 95 – 140 km</td>
<td>3-5%</td>
</tr>
</tbody>
</table>

* Applies to daytime, nighttime and twilight

Potential - High altitudes still contaminated by “hysteresis” and off-axis scatter. Corrections expected to reduce uncertainty to “potential” values.
# SABER Temperature and Constituent Estimated and Observed Precisions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Range</th>
<th>Estimated Precision</th>
<th>Observed In-Orbit Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>10 – 100 km</td>
<td>0.5K, 15 - 65 km</td>
<td>1K, 15 - 65 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1K, 65 - 75 km</td>
<td>2K, 65 - 75 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2K, 75 - 100 km</td>
<td>5K, 75 - 100 km</td>
</tr>
<tr>
<td>O$_3$ (9.6 $\mu$m)</td>
<td>15 – 100 km</td>
<td>5%, 15 - 65 km</td>
<td>5%, 15 - 65 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20%, 65 - 90 km</td>
<td>20%, 65 - 90 km</td>
</tr>
<tr>
<td>O$_3$ (1.27 $\mu$m)</td>
<td>50 – 95 km</td>
<td>10%, 55 - 85 km</td>
<td>10%, 55 - 85 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15%, 85 - 95 km</td>
<td>5%, 85 - 95 km</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>15 – 80 km</td>
<td>10%, 20 - 65 km</td>
<td>10%, 20 - 65 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25%. 65 - 80 km</td>
<td>25%. 65 - 80 km</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>65-100 km</td>
<td>10%, 65 - 100 km</td>
<td>10%, 65 - 100 km</td>
</tr>
</tbody>
</table>
## SABER Energetics (Energy Loss Rate)
Estimated and Observed Precisions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement Range</th>
<th>Estimated Precision</th>
<th>Observed In-Orbit Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH(v), 1.06 $\mu$m</td>
<td>80 – 100 km</td>
<td>0.5%, 80 - 90 km</td>
<td>1.0%, 80 - 90 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%, 90 - 100 km</td>
<td>10%, 90 - 100 km</td>
</tr>
<tr>
<td>OH(v), 2.10 $\mu$m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O$_2$ ($^1\Delta$)</td>
<td>50 – 105 km</td>
<td>0.05%, 50 - 70 km</td>
<td>0.05%, 50 - 70 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2%, 70 - 80 km</td>
<td>0.2%, 70 - 80 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1%, 80 – 90 km</td>
<td>3.0%, 80 – 90 km</td>
</tr>
<tr>
<td>O$_3$ (9.6 $\mu$m)</td>
<td>15 – 100 km</td>
<td>0.5%, 50 - 70 km</td>
<td>1.2%, 50 - 70 km</td>
</tr>
<tr>
<td>(Night)</td>
<td></td>
<td>2%, 70 - 90 km</td>
<td>5.0%, 70 - 90 km</td>
</tr>
<tr>
<td>CO$_2$ (15 $\mu$m)</td>
<td>15 – 120 km</td>
<td>3%, 80 - 100 km</td>
<td>5.0%, 80 - 100 km</td>
</tr>
<tr>
<td>NO</td>
<td>90 – 180 km</td>
<td>3%, 100 - 150 km</td>
<td>1.4%, 100 - 150 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%, 150 – 170 km</td>
<td>5.0%, 150 – 170 km</td>
</tr>
<tr>
<td>CO$_2$ (4.3 $\mu$m)</td>
<td>85 – 150 km</td>
<td>10%, 95 - 140 km</td>
<td>4.0%, 95 - 140 km (Day)</td>
</tr>
<tr>
<td>(Day)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SABER Instrument understanding near a mature stage

- Substantial progress made in removing known artifacts arising due to instrument effects
  - Made important corrections to IFC BB emissivities; T, O$_3$, H$_2$O
  - Knowledge of channel vertical alignment shown to be accurate
  - Moon scans provided excellent knowledge of off-axis signals due to FOV side lobes and mirror scatter
  - Detector focal plane ice build-up due to “trapped” water vapor “in-hand”
  - High altitude radiance bias in short wave channels; 20 x noise up, 7 x noise down scan
  - Possible O$_3$ spectral effect remaining
SABER Focal Plane Channel Locations

# 4  O₃ 9.3 μm

# 5  H₂O 6.8 μm

# 1  CO₂⁻ N 15.2 μm

# 3  CO₂⁻ W 15.0 μm

# 8  OH(A) 2.07 μm

# 6  NO 5.3 μm

# 2  CO₂⁻ W 15.0 μm

# 7  CO₂ 4.26 μm

# 9  OH(B) 1.64 μm

# 10  O₂(¹Δ) 1.28 μm

2 km @ 60 km

1.49°
Effects of off-axis scatter on high altitude Signals in the OH and O2(1\(\Delta\)) channels

Examples of Cloud and No-Cloud
Scans for Channels 9 and 10
SABER CO$_2$W channel Lunar scan FOV Data

FOV (Measured and Derived Versions)

Channel 3: CO$_2$(W)

- Lab Original
- Lab Refined (01.01)
- Lab + Lunar (01.02)

Intensity

Angle (degrees)
SABER Lunar and Laboratory derived FOV functions
Calculated water ice transmission compared to observed SABER values

1 µm thick ice layer

Detector degradation observed from 17 Jan 02 to 25 Apr 02 (98 days)
SABER CO$_2$ W Responsivity Changes Since Launch

![Graph showing responsivity changes over time for different channels.](image)
SABER responsivity slopes are steadily decreasing after each power down
SABER Up and Down Scan Radiance Comparison for the $O_2(^1Δ)$ channel

Date: 2002185, Orbit 03094
Channel 10  Day
SABER O₃ channel spectral response data
Data Reduction and Analysis Techniques
Non-LTE Retrieval
and
SABER Algorithms Understanding

Martin G. Mlynczak
SABER and Non-LTE

- SABER observes IR emission from CO$_2$, O$_2$, H$_2$O, NO, O$_3$ and OH

- The vibration-rotation and electronic transitions observed depart from local thermodynamic equilibrium above ~ 45 km

- SABER team members have spent last 7 years focused on developing the operational algorithms
  - Five kinetics papers published in GRL
  - Led to 7 proposals funded by NASA/NSF/Int’l Agencies for improvements in specific processes (e.g., O-NO; O-CO2)

- SABER team experience in non-LTE dates back 20 years
  - 2 PhD’s earned in non-LTE (Lopez-Puertas; Mlynczak)
  - Over 50 articles in literature, 1 book, on non-LTE from SABER team

- Current operational algorithms rigorously incorporate full non-LTE in forward and inverse modeling
CO$_2$ Non-LTE Modeling
For Retrieval of Kinetic Temperature and Carbon Dioxide Concentration
Non-LTE Tk/CO$_2$ Retrieval and Algorithm Development

**Non-LTE Tk/CO$_2$ Retrieval Algorithm Components**

1. **Forward Model**
   a) Limb Radiance Model
      - CO$_2$ 15 $\mu$m channel: 19 vibration-rotation band transitions
      - CO$_2$ 4.3 $\mu$m channel: 17 vibration-rotation band transitions
      - All bands in non-LTE
   b) CO$_2$ non-LTE Model
      - Vibrational state populations characterized by vibrational temperature (Tv)
      - Non-LTE source functions (related to Tv’s) determined from self-consistent solution of radiative transfer equation and steady-state statistical equilibrium equations
      - 42 vibrational states (Tv’s) required to simulate non-LTE limb emission in SABER CO$_2$ 15 $\mu$m and CO$_2$ 4.3 $\mu$m radiance channels.

2. **Inverse Model (relaxation scheme)**
   - Must deal with the severe nonlinear radiative transfer effects in iterative scheme.
   - Must deal with highly non-local coupling of different atmospheric regions (both vertical and horizontal) in limb emission simulation.
CO$_2$, O$_2$, N$_2$, and H$_2$O States in $T_K$/CO$_2$ Retrieval

Lopez-Puertas et al., 1991
Mertens et al., 2003
SABER Operational T(p)/CO₂ Retrieval Algorithm

1. **Begin Retrieval**
   - Two-channel LTE T(p) Retrieval
     - CO₂N/W channels
     - Pressure registration
     - Initial T/CO₂ profiles

2. **Start NLTE Retrieval from lower boundary**
   - (Z₀, T₀, P₀)
   - CO₂N channel: T(p)
   - 4.3 µm channel: CO₂ vmr

3. **Retrieve T via onion-peel**
   - Match CO₂N radiance
   - Adjust T by optimal estimation
   - Ignore hydrostatics

4. **Rebuild Pressure using Barometric Law**

5. **Compare current/previous T profiles**
   - T profiles relaxed?
     - YES
       - Calculate Tᵥ’s using CO₂ Tᵥ Model
       - Rebuild Pressure using Barometric Law
       - Compare current/previous CO₂ profiles
         - CO₂ profiles relaxed?
           - YES
             - NLTE CO2 vmr Retrieval
               - Retrieve CO₂ vmr via onion-peel
                 - Match 4.3 µm channel radiance
                 - Adjust CO₂ by optimal estimation
           - NO
             - Update Tᵥ’s using CO₂ Tᵥ Model
             - Rebuild Pressure using Barometric Law
             - Compare current/previous T profiles
               - T profiles relaxed?
                 - YES
                   - NLTE T(p) Retrieval
                 - NO
                   - Update Tᵥ’s using CO₂ Tᵥ Model
                   - Rebuild Pressure using Barometric Law
                   - Compare current/previous T profiles

6. **End Retrieval**
H$_2$O NLTE modeling
For Retrieval of H$_2$O Concentrations
**Non-LTE H₂O Retrieval Algorithm Components**

1. **Forward Model**
   a) **Limb Radiance Model (6.8 µm channel)**
      - H₂O major isotopic 6.3 µm fundamental and first hot bands are modeled individually.
      - Remaining H₂O bands are modeled as one pseudo band.
      - Emission from CH₄, O₂ (lines + continuum), CO₂, and O₃ are included as well.
      - H₂O major isotopic 6.3 µm fundamental and first hot bands are in non-LTE.
   b) **H₂O non-LTE Model**
      - Vibrational state populations characterized by vibrational temperature (Tv).
      - Non-LTE source functions (related to Tv’s) determined from self-consistent solution of radiative transfer equation and steady-state statistical equilibrium equations
      - 8 vibrational states (Tv’s) required to simulate non-LTE limb emission in SABER 6.8 µm radiance channel

2. **Inverse Model (relaxation scheme)**
   - Must deal with nonlinear radiative transfer effects in iterative scheme.
   - Must deal with non-local coupling of different atmospheric regions (both vertical and horizontal) in limb emission simulation.
H$_2$O, O$_2$, and O$_3$ States in H$_2$O Retrieval

Lopez-Puertas et al., 1995
Mertens et al., 2001
**SABER Operational Non-LTE H$_2$O Retrieval Algorithm**

**Begin Retrieval**

- Initialize a priori data
  - climatology
  - previous scan

**Calculate Tv’s using H$_2$O Tv Model**

**Retrieve H$_2$O vmr via onion-peel**
- Match 6.3 µm radiance
- Adjust H$_2$O by optimal estimation

**Update Tv’s using H$_2$O Tv Model**

**Compare current/previous H$_2$O profiles**

**YES**

- H$_2$O profiles relaxed?

**NO**

**Compare current/previous H$_2$O profiles**

**Retrieval**

**End Retrieval**

**NLTE H$_2$O Retrieval**
$O_2(^1\Delta)$ NLTE modeling
For Retrieval of Ozone Concentrations
Non-LTE O$_3$ Retrieval from O$_2$(1$\Delta$) Algorithm Development

Non-LTE Ozone from O$_2$(1D) Retrieval Algorithm Components

1. Weak-Line Inverse Model (z > 65 km)
   a) Abel inversion applied to measured radiance
   b) “Unfilter” factor applied to give full band emission rate
   c) Airglow-Ozone relation applied to derive ozone

2. Airglow – Ozone Model
   a) Includes sources related to ozone photolysis
   b) Includes sources related to O2 photolysis
   c) Includes sources related to O2 excitation

3. Strong-Line Model (z < 65 km)
   a) O$_2$ mixing ratio assumed 0.21
   b) Retrieve O$_2$(1$\Delta$) “electronic” temperature
   c) Derive O$_2$(1$\Delta$) volume emission rate
   d) Apply airglow-ozone model to derive ozone
Oxygen Dayglow Production Mechanism

After Mlynczak et al., 1993
O$_3$ 9.6 $\mu$m NLTE modeling
For Retrieval of Ozone Concentrations
Non-LTE 9.6 $\mu$m Ozone Retrieval Algorithm Development

Non-LTE Ozone Retrieval Algorithm Components

1. Forward Model
   a) Limb Radiance Model
      - Ozone 9.6 $\mu$m channel: 11 vibration-rotation band transitions of O$_3$
      - CO$_2$ 9.4 $\mu$m “laser band” transition
      - All bands in non-LTE

   b) O$_3$ non-LTE Model
      - Vibrational state populations characterized by vibrational temperature (Tv)
      - Non-LTE source functions (related to Tv’s) determined from steady-state statistical equilibrium: including chemical pumping, spontaneous emission, collisional quenching and excitation, and radiative excitation
      - 133 vibrational state populations computed; all states below O$_3$(007); includes

2. Inverse Model (relaxation scheme)
   - Onion peel with Tvibs updated during each step as necessary.
   - Relaxation stops with agreement between measured, modeled radiances
   - Does not possess the non-linearity in the non-LTE region as does CO$_2$ and H$_2$O
Chemical Pumping

Collisional quenching
~ 2000 transitions

Spontaneous emission
~ 120 transitions

Radiative excitation
4 transitions

O₃ 9.6 µm Non-LTE Model Summary

All 133 Energy Levels below O₃(007)

6850 of 8800 cm⁻¹ of vibrational well

Tvibs computed for 11 bands in SABER filter

Retrieval also includes CO₂ laser bands

After Mlynczak and Drayson, 1991
SABER Operational Non-LTE O₃
9.6 μm Retrieval Algorithm

Begin Retrieval

Initialize a priori data
• climatology
• previous scan

Calculate Tv’s using O₃ Tv Model

Update Tv’s using O₃ Tv Model

Retrieve O₃ vmr via onion-peel
• Match 9.6 μm radiance
• Adjust O₃ by optimal estimation

Compare current/previous O₃ profiles

O₃ profiles relaxed?

YES

NO

End Retrieval

NLTE O₃ Retrieval
Volume Emission Rate Derivation
SABER Volume Emission Rate Derivation

- SABER also derives the volume emission rate (photons cm\(^{-3}\) s\(^{-1}\)) of NO(5.3 \(\mu\)m), O\(_2\)(1.27 \(\mu\)m), OH(1.6 \(\mu\)m), and OH(2.0 \(\mu\)m)

- SABER is a broadband radiometer
  - Not all lines in each band observed
  - Spectral filter results in non-uniform weighting of observed lines

- SABER applies “unfilter” factor to go from in-band volume emission rates to total band emission rates

- Rates computed over a range of rotational, vibrational, and electronic temperatures, as appropriate

- Both the in-band (“filtered”) and total band (“unfiltered”) emission rates are provided in the operational data set.
SABER Limb Radiance Simulation $Z_{\tan} = 170$ km
(quiescent conditions)

Simulated Limb Radiance at 170 km (Channel #6)

Contribution of the Fundamental and First Hot Bands of NO

Wavenumber (cm$^{-1}$)

Radiance (W/m$^2$/sr/cm$^{-1}$)
Line Intensities of $O_2(a\leftarrow X)$ vs. Temperature

Line Intensities of $O_2$ at Several Atmospheric Temperatures

- 180 K (90 km)
- 230 K (65 km)
- 250 K (110 km)
- SABER filter

Strength (cm$^{-1}$/molecule*cm$^{-2}$) vs. Wavenumber (cm$^{-1}$)
SABER measures the OH(9-7) + OH(8-6) emission rate at 2.0 µm
“Unfilter” Factor Definition

\[ U(z) = \frac{\text{layer radiance}}{\text{layer radiance} \times \text{spectral response}} \]

\[ U(z) = \frac{\sum_{\text{all lines}} S_i J_i}{\sum_{\text{all lines}} S_i J_i \phi_i} \]

- \( S_i = \) non-LTE line strength of \( i^{th} \) line
- \( J_i = \) non-LTE source function of \( i^{th} \) line
- \( \phi_i = \) spectral response at wavenumber of \( i^{th} \) line
Derivation of Volume Emission Rate from Limb Radiances

Measure Limb Radiance

\[ R(Z_T) \]

(W m\(^{-2}\) sr)

4\(\pi\) * Abel Inversion

\[ E(z) = 4\pi * A(R(Z_T)) \]

(W m\(^{-3}\), in band)

Unfilter

\[ E'(z) = U(z) * E(z) \]

(W m\(^{-3}\), all lines)
Animation – Solar Storms of April 2002
Vertically Integrated Energy Loss & Vertical Energy Loss Profile NO 5.3 μm -- Southern Hemisphere
Thermospheric Energy Loss
NO 5.3 μm
Thermospheric Energy Loss
NO 5.3 µm
Thermospheric Energy Loss
NO 5.3 \( \mu \text{m} \)
Thermospheric Energy Loss
NO 5.3 μm
Thermospheric Energy Loss

NO 5.3 $\mu$m
Thermospheric Energy Loss
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Thermospheric Energy Loss
NO 5.3 µm
Thermospheric Energy Loss
NO 5.3 µm
Thermospheric Energy Loss

NO 5.3 μm
SABER Algorithm Summary

- SABER now operationally retrieving T, O$_3$(9.6), O$_3$(1.27 $\mu$m), H$_2$O, CO$_2$, and NO(ver), O$_2$(ver), and OH(1.6 $\mu$m, 2.0 $\mu$m ver)

- Legacy radiative transfer codes (LINEPAK, BANDPAK) previously used in LIMS, UARS, CRISTA employed for operational radiative transfer calculation that includes the non-LTE

- Full non-LTE applied in all retrievals above mid-stratosphere

- Intent is to update non-LTE (kinetics, etc.) if necessary

- Goal is to assess quality of all non-LTE products by
  - Internal self consistency
  - Validation with all available correlative measurements
  - Comparison with numerical models

Realization of operational non-LTE is culmination of years of SABER team effort
Data Quality and Data Processing Status
Temperature measured during Macwave

- Na Lidar July 4 20:23 UT (69.3 N, 16.0 E)
- Na Lidar July 4 21:50 UT (69.3 N, 16.0 E)
- Na Lidar July 4 23:33 UT (69.3 N, 16.0 E)
- Na Lidar July 5 26:33 UT (69.3 N, 16.0 E)
- Na Lidar July 5 27:00 UT (69.3 N, 16.0 E)
- Na Lidar July 5 30:75 UT (69.3 N, 16.0 E)
- SABER July 4 23:50 UT (71.6 N, 18.7 E)
NLTE SABER and HALOE O₃
SABER 9.6μm and 1.27μm daytime O₃ cross section on July 4, 2002
SABER 9.6\(\mu m\) and 1.27\(\mu m\) O3 difference cross sections on July 4, 2002 and March 21, 2003

July 4, 2002  
March 21, 2003
NLTE SABER 9.6 μm and 1.27 μm O₃
For January 17, 2003 at 45°N
NLTE SABER and HALOE O₃
SABER V1.04 Ozone global plot on July 9, 2002
LTE SABER and HALOE H₂O

HALOE H₂O vs. SABER H₂O (May-July 2002 - nighttime) - SH mid lat.
LTE SABER and HALOE H$_2$O

June 29 to July 9 – SABER – V1.03

H$_2$O Pressure vs Latitude
Sunset 12-MAY to 05-JUL-2002
SABER retrieved CO2 cross section compared to TIME-GCM for September

SABER retrieved CO2 for September 22, 2003

TIME-GCM Model CO2 for September

SABER retrieved CO2 for September 22, 2003
Improvements from inclusion of CO2 line mixing and adjustment of pressure registration window

Significant $T$, $O_3$, and $H_2O$ changes in right direction
SABER Data Quality Status

- Good confidence in retrieved temperatures up to ~95 km
  - NLTE data especially important outside the tropics
- NLTE O₃ agrees with HALOE to within ~ 20% for ~ 20 km to 60 km. High bias in the mesosphere with respect to HALOE.
- LTE H₂O in the stratosphere biased high with respect to HALOE
- Broad scale O₃ and H₂O morphology appears to be reasonable but quality of small scale variability is unknown.
- Radiance quality is very good but some biases exist for short wave channels, i.e. OH(A), OH(B), O₂(¹Δ)
- Recent retrievals using line mixing and optimized pressure registration window shows significant improvements
Operational processing (V1.04) of NLTE temperature, O$_3$ from O$_2$(1$\Delta$), and VERs for NO, OH(A), OH(B) and O$_2$(1$\Delta$), with the “unfilter” factor included started Dec 4, 2003

Product Availability Notices (PANs) available for:

Level 1B and 2A (LTE) V1.04
- Level1B Status: 516 Days
- Level2A Status: 520 Days
Scientific Usefulness of the Processed Data
NLTE SABER zonal mean temperature July 4, 2002 showing double mesopause structure

NLTE temperature shows double mesopause structure

LTE temperature shows little double mesopause structure

(Mertens et al, 2003)
SABER data show presence of mesospheric chemical heating on June 4, 2002

Chemical heating present every day of yaw period analyzed for May – July, 2002
SABER (m,f) Spectra at ~71 km show “quasi-2-day” wave (Garcia, 2003)

Large 2-day wave amplitudes are seen around summer solstice

Jan-Feb 2002 at 36 S
(m,f) at lat=-36.00, z=10.10 sh, max=1.3
bw=3  25 Jan – 24 Feb 2002

Jun-Jul 2002 at 36 N
(m,f) at lat=36.00, z=10.10 sh, max=2.0
bw=3  31 May – 10 Jul 2002

Variance is present along a line of constant phase speed; largest for m = 3, 4 near 0.5 cpd

~ 70 m/s
SABER “quasi-2-day” wave amplitude for 2002 and 2003 (Garcia, 2004)

\( \lambda = 3, \text{ June 15-July 14, 2002} \)

\( \lambda = 3, \text{ June 14-July 14, 2003} \)

\( \lambda = 4, \text{ June 15-July 14, 2002} \)

\( \lambda = 4, \text{ June 14-July 14, 2003} \)
October – November 2003 Solar Storm
Oct – Nov, 2003 solar storm shows large effect on NO emission at 125 km

NO VER before storm
October 12, 2003

NO VER near storm peak
October 31, 2003
NO mixing ratio profiles measured by HALOE on the UARS Platform
HALOE daily zonal mean thermospheric NO profiles – Oct 2003

Latitude = 60S to 80S

Altitude (km)

NO Mixing Ratio (ppbv)

NO profiles for different dates from Oct 12 to Nov 1.
HALOE daily zonal mean thermospheric NO profiles – Nov 2003

Latitude = 60S to 80S

NO Mixing Ratio (ppbv)

Altitude (km)
NO VER time series at 125 km compared with X-ray, electron and proton fluxes from GOES and TIMED/SEE, Ap Index
Daily averaged NO VERs at 125 km, 70°N - 80°N, and Ap index

SABER Avg NO VER
125 km 70°N - 80°N

Ap Index

Corr. Coeff. 73%
SABER 125 km northern hemisphere NO VERs on October 30 2003 with magnetic coordinates.
SABER NO Volume Emission Rates during the April, 2002 and October, 2003 Solar Storms

NO VERs at 110 km, April 18, 2002, near peak of solar storm

NO VERs at 110 km, October 31, 2003, near peak of solar storm
SABER 4.3-μm Channel Solar Storm response compares well with GUVI LBH-2
Comparison of SABER NO 5.3 µm Energy Loss Rates for April, 2002 and October, 2003 solar storms

October, 2003
82º N

April, 2002
82º S

Peak energy loss rates are comparable for the two storms
Energy loss rate comparison for SABER NO 5.3 \(\mu\text{m}\)
And calculated TIME-GCM/ASPEN [O] at 63 \(\mu\text{m}\)

April, 2002 solar storm for 77.5\(^\circ\)S

\[\text{NO is dominant ‘thermostat’ emitter in thermosphere}\]
SABER Temperature Tidal Structures
SABER CO$_2$ 15-$\mu$m Emission Shows Signature of Diurnal Tide

### Typical equatorial ascending / descending radiance profiles and difference (21 Mar 2002)

- **Equatorial radiance $\Delta'$ s over 34 days (~8.8 hr LT $\Delta'$)**
  - Vertical wavelength 22-25 km
  - Phase fronts descend with LT at ~ 22 km/day)
  - Consistent with interpretation as diurnal tide
Extended Mission Research Tasks
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<th>Year 1</th>
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<th>Year 4</th>
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<td>Geomagnetic disturbance penetration</td>
<td>Mean circulation pattern and effects on energy balance</td>
<td>Solar cycle effects on geomagnetic disturbance penetration</td>
<td>Solar cycle dependence of mean circulation</td>
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<tr>
<td>Dominant wave features and space/time Δ’s</td>
<td>Processes controlling CO₂, H₂O, O₃, O</td>
<td>Solar cycle dependence of dominant wave features</td>
<td>Solar cycle dependence of chemical processes</td>
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<td>Relative importance of different heat sources/sinks</td>
<td>Determination of the turbopause location and variation</td>
<td>Solar cycle dependence of different heat sources and sinks</td>
<td>Solar activity effects on MLTI seasonal basic structure</td>
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<td>Relative importance of process controlling wave activity</td>
<td>Solar rotation effects on structure and chemistry</td>
<td>Study of low freq. forcing from below (e.g. QBO)</td>
<td>Solar cycle dependence of solar rotation effects on structure/chem.</td>
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<tr>
<td>Variation of NO and CO₂ cooling</td>
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## Extended Mission Research Tasks – Year 1

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<tr>
<th>Priority</th>
<th>Research Description</th>
<th>Data Needed</th>
<th>Source</th>
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<tbody>
<tr>
<td>1</td>
<td>Determine how far in latitude and altitude geomagnetic disturbance effects penetrate and assess their effects on basic atmospheric structure and properties</td>
<td>T(Z), NO, H$_2$O, O$_3$, OH(A), OH(B), CO$_2$(15\text{$\mu$m}), O$_2$(^1\Delta), CO$_2$(4.3\text{$\mu$m})</td>
<td>SABER</td>
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<td>Auroral input</td>
<td>GUVI</td>
</tr>
<tr>
<td>1</td>
<td>Determine the dominant wave features in the MLTI and their spatial and temporal variations</td>
<td>T(Z), CO$_2$, O$_3$</td>
<td>SABER</td>
</tr>
<tr>
<td>1</td>
<td>Determine the relative importance of different atmospheric heat sources and sinks</td>
<td>NO, OH(A), OH(B), O$_2$(^1\Delta), O$_3$, O, CO$_2$(4.3\text{$\mu$m}), CO$_2$(15\text{$\mu$m})</td>
<td>SABER</td>
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<td>O</td>
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<th>Priority</th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>Determine the relative importance of the various processes that generate and control changes in planetary, gravity and tidal wave characteristics</td>
<td>T(Z)</td>
<td>SABER</td>
</tr>
<tr>
<td>2</td>
<td>Determine how CO\textsubscript{2} and NO cooling vary and evaluate the role of O in enhancing cooling rates</td>
<td>CO\textsubscript{2}, NO, O</td>
<td>SABER</td>
</tr>
<tr>
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<td>O</td>
<td>GUVI</td>
</tr>
<tr>
<td>2</td>
<td>Use observations of rocket and shuttle exhaust as an indicator of lower thermospheric transport</td>
<td>H\textsubscript{2}O</td>
<td>SABER</td>
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<td>Winds</td>
<td>TIDI</td>
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## Extended Mission Research Tasks – Year 2

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<th>Priority</th>
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<th>Data Needed</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Determine the mean circulation pattern and dynamic transport of $\text{H}_2\text{O}$ and $\text{CO}_2$ and assess the role of these effects on energy balance and the mean state</td>
<td>$T(Z)$, $P(Z)$, $\text{H}_2\text{O}$, $\text{CO}_2$, $\text{OH}$, $\text{NO}$, $\text{O}_2(^1\Delta)$, Winds</td>
<td>SABER, TIDI</td>
</tr>
<tr>
<td>1</td>
<td>Determine what processes control the global distributions of $\text{CO}_2$, $\text{O}$, $\text{O}_3$ and $\text{H}_2\text{O}$ and specifically when and where photochemistry plays an important role</td>
<td>$\text{CO}_2$, $\text{O}$, $\text{O}_3$, $\text{H}_2\text{O}$, $\text{O}$</td>
<td>SABER, GUVI, SEE, TIDI</td>
</tr>
<tr>
<td>2</td>
<td>Determine the location of the $\text{CO}_2$ turbopause, its spatial and temporal variations and the role of waves in defining the turbopause</td>
<td>$T(Z)$, $\text{CO}_2$</td>
<td>SABER</td>
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<tr>
<td>2</td>
<td>Analyze the effects of solar rotation on the basic structure and chemistry of the MLTI</td>
<td>$T(Z)$, $P(Z)$, $\text{O}_3$, $\text{H}_2\text{O}$, $\text{O}$, $\text{O}$</td>
<td>SABER, GUVI, SEE</td>
</tr>
<tr>
<td>Priority</td>
<td>Research Description</td>
<td>Data Needed</td>
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<tr>
<td>1</td>
<td>Determine the effect of low frequency forcing from the lower atmosphere (e.g. ENSO, QBO) on MLTI composition and structure</td>
<td>T(Z), P(Z), H₂O, O₃, OH(A), OH(B), O₂(¹Δ), CO₂(4.3µm), CO₂(15µm), O</td>
<td>SABER</td>
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<td>O</td>
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<td>Solar input</td>
<td>SEE</td>
</tr>
<tr>
<td>1</td>
<td>Determine the solar cycle dependence of the dominant wave features in the MLTI and their spatial and temporal variations</td>
<td>T(Z), CO₂, O₃</td>
<td>SABER</td>
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<td>Winds</td>
<td>TIDI</td>
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<td>Solar input</td>
<td>SEE</td>
</tr>
<tr>
<td>1</td>
<td>Determine the solar cycle dependence of the relative importance of different atmospheric heat sources and sinks</td>
<td>NO, OH(A), OH(B), CO₂(15µm), O₂(¹Δ), O₃, CO₂(4.3µm)</td>
<td>SABER</td>
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## Extended Mission Research Tasks – Year 3
(Feb. 2006 – Jan. 2007)

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<tbody>
<tr>
<td>2</td>
<td>For different solar activity conditions, determine how far in latitude and altitude geomagnetic disturbance effects penetrate.</td>
<td>T(Z), P(Z), H₂O, O₃, OH(A), OH(B), O₂(¹Δ), CO₂(4.3μm), CO₂(15μm), O</td>
<td>SABER</td>
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<tr>
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<th>Solar input</th>
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## Extended Mission Research Tasks – Year 4

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<tbody>
<tr>
<td>1</td>
<td>Determine how the global distributions of CO₂, O, O₃ and H₂O vary with the solar cycle</td>
<td>CO₂, O, O₃, H₂O</td>
<td>SABER</td>
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<td>O</td>
<td>GUVI</td>
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<tr>
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<td>Solar input</td>
<td>SEE</td>
</tr>
<tr>
<td>1</td>
<td>Determine how the mean circulation pattern and dynamic transport of H₂O and CO₂ vary with the solar cycle</td>
<td>T(Z), P(Z), H₂O, CO₂, OH, NO, O₂(¹Δ)</td>
<td>SABER</td>
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<td>Winds</td>
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<td>Solar input</td>
<td>SEE</td>
</tr>
<tr>
<td>2</td>
<td>Analyze the altitude and latitude dependence of the influence of solar activity on seasonal MLTI basic structures</td>
<td>T(Z), P(Z)</td>
<td>SABER, GUVI</td>
</tr>
<tr>
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<td>Solar input</td>
<td>SEE</td>
</tr>
<tr>
<td>2</td>
<td>Determine how the effects of solar rotation on the basic structure and chemistry of the MLTI vary with solar cycle</td>
<td>T(Z), P(Z), O₃, H₂O, O</td>
<td>SABER</td>
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SABER Prospects for the Future
The SABER instrument performance in orbit is excellent. Routine periodic turn-off needed to remove detector/filter focal plane ice but effect is small now and of no consequence for data processing. Field-of-View effects addressed using orbital data and FOV knowledge is well in-hand. Temperature data quality is excellent and agrees well with correlative data. NLTE temperature ZM cross section shows clear double mesopause structure. Diurnal tide and “Quasi 2-day” wave signatures present. Mesosphere chemical heating present on all days analyzed. NO radiances show strong effects due to the April 2002 and Oct 2003 solar storms – large NO changes and major cooling. Strong NO VER correlation with Ap index and enhancements align with magnetic coordinates.