

1 **Sounding of the Atmosphere using Broadband Emission Radiometry (SABER):**

2 **Instrument and Science Measurement Description**

3 **The SABER Team:**

4 Roy Esplin (Space Dynamics Laboratory, Logan, UT)

5 Martin Mlynczak (NASA Langley Research Center, Hampton, VA)

6 James Russell (Hampton University, Hampton, VA)

7 Larry Gordley (GATS Inc., Newport News, VA)

8 Doran Baker (Utah State University, Logan, UT (deceased))

9 Kenneth Beaumont (NASA Langley Research Center, Hampton, VA)

10 Guy Beaver (GATS, Inc., Newport News, VA (formerly))

11 Christopher Brown (NASA Langley Research Center, Hampton, VA)

12 Steven Brown (Space Dynamics Laboratory, Logan, UT)

13 Michael Cisewski (NASA Langley Research Center, Hampton, VA)

14 Todd Denkins (NASA Langley Research Center, Hampton, VA)

15 John Dodgen (NASA Langley Research Center, Hampton, VA (deceased))

16 James Dyer (Space Dynamics Laboratory, Logan, UT (retired))

17 Thomas Eden (LASP, University of Colorado, Boulder, CO)

18 Patrick Espy (Norwegian University of Science and Technology, Trondheim, Norway)

19 Matt Felt (Space Dynamics Laboratory, Logan, UT)

20 Rolando Garcia (National Center for Atmospheric Research, Boulder, CO)

21 Richard Grube (NASA Langley Research Center, Hampton, VA)

22 Glen Hansen (Space Dynamics Laboratory, Logan, UT)

23 Scott Hansen (Space Dynamics Laboratory, Logan, UT)

24 Susan Henriksen (NASA Langley Research Center, Hampton, VA (retired))

25 Linda Hunt (Science Systems and Applications, Inc., Hampton, VA)

26 William Grose (NASA Langley Research Center, Hampton, VA (retired))

27 Ron Huppi (Space Dynamics Laboratory, Logan, UT (retired))

28 Antony Jalink (NASA Langley Research Center, Hampton, VA (deceased))
29 Mark Jensen (Space Dynamics Laboratory, Logan, UT)
30 Scott Jensen (Orion Space Solutions, Louisville, CO)
31 Gretchen Lingenfelter (NASA Langley Research Center, Hampton, VA (retired))
32 Manuel Lopez Puertas (Instituto de Astrofisica de Andalucia, Granada, Spain)
33 Benjamin Marshall (GATS, Inc., Newport News, VA)
34 Mark Melbert (GATS, Inc., Newport News, VA (formerly))
35 Christopher Mertens (NASA Langley Research Center, Hampton, VA)
36 James Miller (NASA Langley Research Center, Hampton, VA (deceased))
37 Keith Paskett (Space Dynamics Laboratory, Logan, UT)
38 Gregory Paxton (GATS, Inc., Newport News, VA)
39 Frank Peri (NASA Langley Research Center, Hampton, VA)
40 James Petersen (Space Dynamics Laboratory, Logan, UT)
41 Richard Picard (Air Force Resarch Laboratory, Hanscom AFB, (retired))
42 Ellis Remsberg (NASA Langley Research Center, Hampton, VA)
43 Donald Robinson (NASA Langley Research Center, Hampton, VA (deceased))
44 Raymond Roble (National Center for Atmospheric Research, retired)
45 William Roettker (Ball Aerospace, Boulder, CO)
46 Deron Scott (Space Dynamics Laboratory, Logan, UT)
47 Robert Sherrill (NASA Langley Research Center, Hampton, VA (retired))
48 Andrew Shumway (Space Dynamics Laboratory, Logan, UT)
49 David Siskind (Naval Research Laboratory, Washington, DC, retired)
50 Susan Solomon (Massachusetts Institute of Technology, Boston, MA)
51 John Stauder (Space Dynamics Laboratory, Logan, UT)
52 Kenneth Stone (University of Colorado, Boulder, CO)
53 Charles Stump (NASA Langley Research Center, Hampton, VA (retired))
54 Joe Tansock (Utah State University, Logan, UT)
55 R. Thompson (GATS, Inc., Newport News, VA (retired))

56 Michael Vanek (NASA Langley Research Center, Hampton, VA (retired))
57 Yunfei Wang (GATS, Inc, Newport News, VA (formerly))
58 Jeremy Winick (Air Force Research Laboratory, Hanscom AFB, (retired))
59 Peter Wintersteiner (ARCON Corp., Waltham, MA (retired))
60 James Wells (NASA Langley Research Center, Hampton, VA)
61 John Wells (NASA Langley Research Center, Hampton, VA (retired))
62 James Ulwick (Stewart Radiance Laboratory, Bedford, MA (deceased))
63 Lorin Zollinger (Space Dynamics Laboratory, Logan, UT)

64 **Abstract**

65 SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) is a 10-
66 channel infrared radiometer that is one of four instruments on the NASA TIMED (Thermosphere-
67 Ionosphere-Mesosphere Energetics and Dynamics) satellite mission to study the structure,
68 energetics, chemistry, and dynamics of the Earth's mesosphere and lower thermosphere. The
69 TIMED spacecraft was launched into a 625 km circular polar orbit (74.1° inclination) via a Boeing
70 Delta II rocket from Vandenberg Air Force Base on 7 December 2001. SABER continues to
71 operate nominally and collect data routinely as it has for over 21 years. Over 2,200 peer-reviewed
72 journal articles have been published worldwide using SABER data. A list of these articles is
73 included in the Supporting Information accompanying this paper. The Space Dynamics Laboratory
74 (SDL) of Utah State University designed, fabricated, and calibrated the SABER instrument in close
75 collaboration with NASA Langley Research Center, Hampton University, and Global
76 Atmospheric Technologies and Science (GATS). This paper provides a detailed technical
77 description of the SABER instrument, including performance specifications and observed
78 instrument performance.

79 **Plain Language Summary**

80 Earth's mesosphere and lower thermosphere (MLT), approximately 50 to 180 km in
81 altitude or 30 to 110 miles high) was the least explored region of the atmosphere thirty years ago.
82 The MLT is a critical region of Earth's atmosphere as it is the boundary or interface between the
83 space environment and the lower atmosphere. Today the region is referred to as part of the
84 'geospace' environment. To examine the MLT in more detail, NASA developed the
85 Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics or TIMED satellite mission
86 beginning in 1996. Launch of the TIMED satellite occurred in December 2001. One of the four
87 instruments carried by the TIMED satellite is named SABER (Sounding of the Atmosphere using
88 Broadband Emission Radiometry). SABER continues to provide exceptional scientific results and
89 is still routinely collecting data more than 21 years after launch. This paper provides a technical
90 description of the SABER instrument.

91 **Key Points**

- 92 1. SABER is an infrared limb sounding instrument observing the Earth's mesosphere and
93 lower thermosphere continuously for over two decades.
- 94 2. SABER was developed through a partnership involving NASA Langley, Space Dynamics
95 Laboratory, Hampton University, and GATS.
- 96 3. SABER is still operational with no reduction in capability and has yielded over 2,200 peer-
97 reviewed journal articles by worldwide authors.

98

99

100 **1. Introduction**

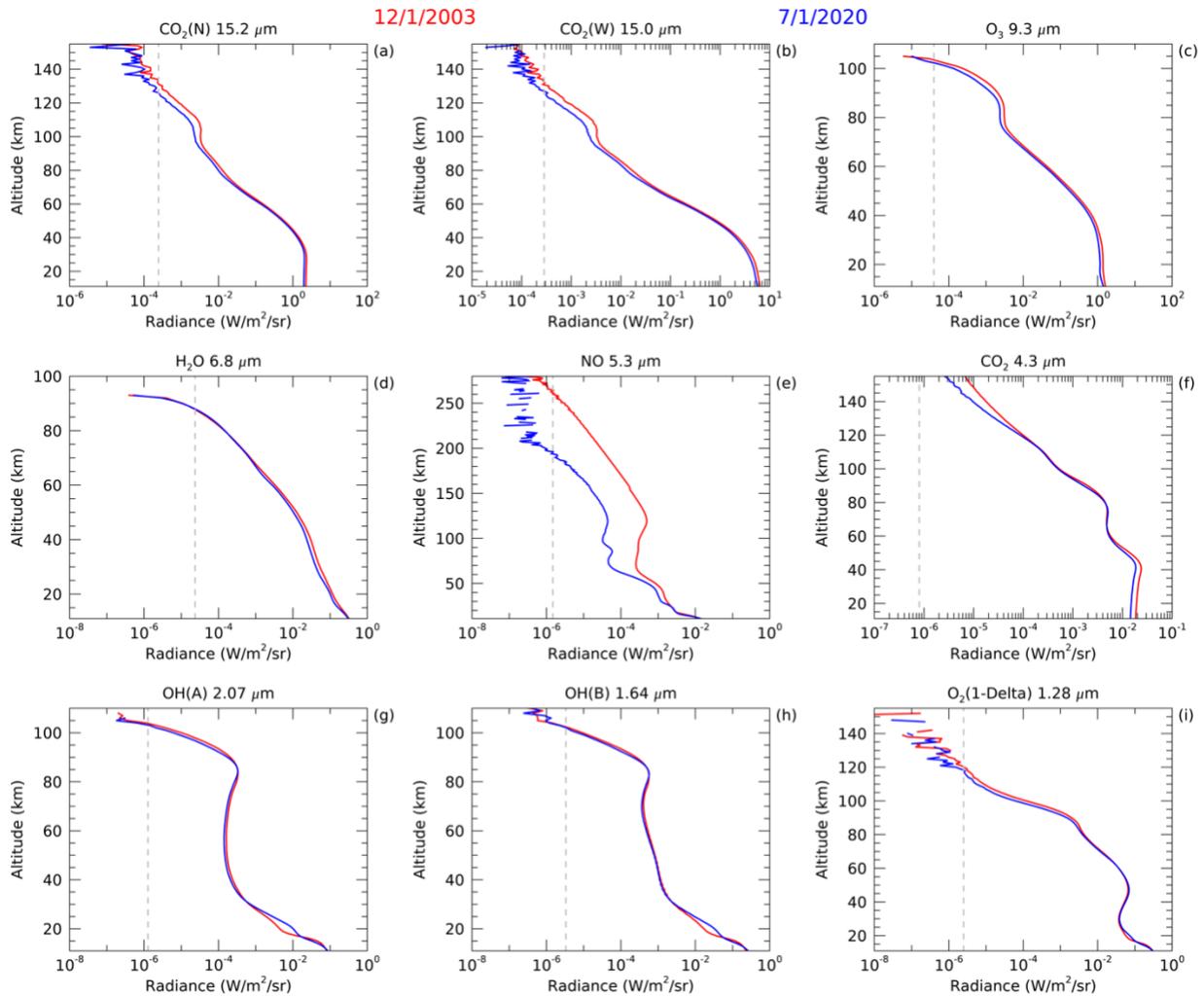
101 This paper provides a detailed technical description of the Sounding of the Atmosphere
102 using Broadband Emission Radiometry (SABER) instrument. SABER is one of four instruments
103 on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite
104 mission developed through the Heliophysics Division of NASA’s Science Mission Directorate.
105 The TIMED mission was developed to conduct the first comprehensive and global examination of
106 the Earth’s mesosphere and lower thermosphere (MLT), nominally the region between 60 and 180
107 km altitude. SABER was proposed in 1992 to the NASA Announcement of Opportunity (AO) for
108 the TIMED mission. The TIMED AO was issued following mission Science Definition Team
109 activities from 1990 to 1991. The TIMED mission entered formulation (Phase C) in October 1996
110 and four instruments were built and shipped for integration onto the TIMED spacecraft by the end
111 of 1999. The SABER instrument was developed under a partnership between the NASA Langley
112 Research Center, the Space Dynamics Laboratory (SDL) of Utah State University, Hampton
113 University, and Global Atmospheric Technologies and Sciences (GATS). The TIMED spacecraft
114 was launched into a 625 km circular orbit (74.1° inclination) via a Boeing Delta II rocket from
115 Vandenberg Air Force Base on 7 December 2001. Routine SABER operations began 22 January
116 2002 and continue to this day with over 98% of all possible data collected. The TIMED mission
117 is currently approved to continue routine operations through September 2023 and the mission team
118 has proposed to NASA to continue another three years through September 2026. TIMED and
119 SABER are among NASA’s longest serving Earth-observing satellites and instruments. Continued
120 observations of the geospace environment are critical as this region is now undergoing long-term
121 change due to increasing carbon dioxide (*Mlynczak et al., 2021, 2023*).

122 The SABER experiment was developed to conduct a comprehensive investigation into the
123 thermal structure and energy balance of the MLT. The major elements of the energy budget are
124 heating due to the absorption of solar radiation; heating due to exothermic chemical reactions that
125 ultimately degrade much of the solar energy to heat; and infrared radiative cooling. *Mlynczak and*
126 *Solomon* (1993) discuss in detail the entire chain of solar energy deposition, airglow (non-cooling)
127 radiative losses, and heating through exothermic chemical reactions. Observations of kinetic
128 temperature (T), ozone (O₃), water vapor (H₂O), carbon dioxide (CO₂), nitric oxide (NO), atomic
129 oxygen (O), and atomic hydrogen (H) are required to fully characterize the radiative energy budget
130 of the MLT (*Mlynczak*, 1996; 1997). From these measurements the vertical profiles of the rates of
131 radiative heating and cooling and rates of heating due to exothermic chemical reactions may be
132 derived. Every day, SABER provides approximately 1,400 profiles each of temperature, minor
133 constituents (O₃, H₂O, CO₂, O, H), and more than 30 individual rates of radiative heating, radiative
134 cooling, and rates of heating due to exothermic chemical reactions.

135 The scientific productivity of SABER has been exceptional. Over 2,200 peer-reviewed
136 journal articles incorporating SABER data have been published worldwide. A list of reference
137 citations to these articles is included in the Supporting Information to this paper. In addition,
138 SABER data have been used in over 80 doctoral dissertations and master's theses, and in more
139 than 120 books or book chapters. Over 1,000 presentations using SABER data have been made at
140 scientific symposia.

141 SABER's success is due to the excellent quality of the infrared limb radiances that it
142 measures. As mentioned earlier, approximately 1,400 profiles of infrared limb radiance (units of
143 W m⁻² sr⁻¹), per each of the 10 channels, are measured daily, resulting in over 100 million
144 individual limb radiance profiles measured to date by SABER. Figure 1 illustrates the remarkable

145 radiometric performance of the SABER instrument. Shown in this figure are orbit-average limb
146 radiance profiles as a function of tangent altitude in each of the 10 SABER channels (described
147 below in more detail). The red profiles are data taken approximately two years after launch in 2003
148 during conditions near the maximum of the 11-year solar cycle. The blue profiles are taken 16.5
149 years later during solar minimum conditions. The vertical dashed line in each figure marks the
150 noise equivalent radiance (NER) value in each channel. The NER measured during ground
151 calibration of SABER are listed later in Section 3.1 in Table 2. The altitude at which the NER line
152 intersects the radiance profile is where the signal-to-noise is equal to unity. SABER routinely
153 observes limb radiance to a minimum upper limit of 100 km and to above 270 km in the nitric
154 oxide (NO) channel during solar maximum conditions.



155

156 **Figure 1.** Orbit average infrared limb radiance profiles (blue, red curves) and the corresponding
 157 noise equivalent radiance (NER, dashed vertical line) in each of SABER's 10 channels. The blue
 158 profiles were measured by SABER on 1 December 2003 and the red profiles on 1 January 2020.

159

160 This paper presents a detailed technical description of the SABER instrument including
 161 description of major subsystems of the instrument and technical performance parameters. The
 162 motivation for this paper is to describe the SABER instrument components and performance to
 163 document this information for future reference and satisfy NASA requirements in this regard.

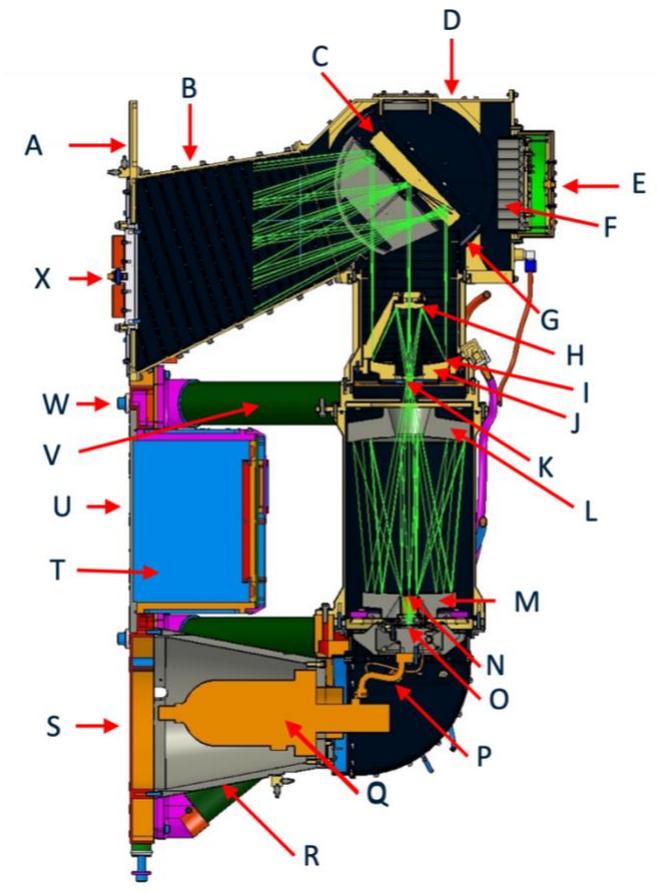
164 The SABER instrument and preliminary calibration performance is described in *Russell,*
165 *Mlynczak, et al., [1999]*. The single most important decision made in the development of SABER
166 was to commit to producing the most accurately calibrated instrument possible for the available
167 resources. This one decision guided parts development, parts testing and selection, instrument
168 thermal and mechanical design, and instrument operations. The decision to focus on calibration
169 resulted in an instrument that is remarkably stable (as discussed in detail in *Mlynczak, Daniels, et*
170 *al., 2020*) and that has lasted well beyond the two-year lifetime envisioned for the TIMED mission.
171 The design and initial performance of SABER is described by *Brown et al. (2006)*. The calibration
172 of SABER is described by *Tansock et al. [2003]*. The present paper describes the instrument and
173 components in much greater detail and provides final instrument design and performance
174 parameters. The complete SABER instrument calibration final report prepared by SDL for NASA
175 Langley is included in the Supporting Information.

176 The remainder of this paper is organized as follows: Section 2 describes the SABER
177 instrument and its operation; Section 3 describes many instrument level parameters including
178 radiometric, optical, and electrical in addition to parameters such as mass and size; Section 4
179 describes twelve major components of the SABER instrument (e.g., the in-flight calibrator and the
180 cryocooler); and the paper concludes with a Summary. Lastly, we note that the success of the
181 SABER instrument is due to the remarkable efforts of many people at the partner organizations.
182 Consequently, this paper contains a large team authorship.

183 **2. The SABER Instrument**

184 Figure 2 shows a computer-generated drawing of the of the SABER instrument and traces
185 the path of light from the scan mirror (C) to the focal plane array (O). Each letter in the figure
186 corresponds to a specific component or part of the instrument, which are listed in the legend to the

187 right of Figure 2. The SABER instrument is 103 cm in height, 60 cm from front to back, and 75
 188 cm side to side. Light enters the instrument from the Earth's limb through the entrance aperture at
 189 point X. Thin green lines in the figure trace the path of the light through the fore-optics baffle (B)
 190 onto the scan mirror (C) which directs the light into a telescope with a series of mirrors (M1
 191 through M4, items H, J, L, M in Figure 2). The scan mirror (C, D) can rotate to view the inflight
 192 calibrator (E, F) that is viewed every four limb scans. The inflight calibrator is a blackbody
 193 maintained at a temperature of 247 Kelvin. The mirror scans high enough to see a space view at
 194 approximately 400 km above the Earth's surface. The space view and the inflight calibrator
 195 provide the two-point reference needed to keep SABER calibrated over the life of the mission.



Letter Identifier	Component
A	Telescope Radiator
B	Fore-Optics Baffle
C	Scan Mirror
D	Scan Mirror Assembly
E	Inflight Calibrator (IFC) Assembly
F	Full-Aperture Blackbody & Jones Sources
G	In-Flight Calibrator Light Trap
H	Secondary Mirror (M2) with Sec. Mirror Baffle
I	Aperture Stop
J	Primary Mirror (M1) with Inner Conical Baffle
K	10 Aperture Chopper
L	Quaternary Mirror (M4)
M	Tertiary Mirror (M3)
N	Lyot Stop
O	Focal Plane Assembly (FPA)
P	Flexible Thermal Strap
Q	Cryocooler
R	Cryocooler Mount
S	Spacecraft Interface plate & cryocooler radiator
T	Electronics Box
U	Electronics Radiator
V	Telescope Support Strut (G-10 Fiberglass)
W	Alignment Cube (Removed before flight)
X	Cover (Ejected after initial outgassing)

196
 197
 198 **Figure 2.** Computer-generated internal view of the SABER instrument.

199 After passing through the series of mirrors the light is focused on the focal plane assembly
200 (O) that contains 10 discrete detectors. An interference filter over each detector provides spectral
201 isolation needed to quantify the infrared emission from CO₂, O₃, H₂O, OH, NO, and O₂(¹Δ). The
202 spectral bandpass for each channel can be seen later in Section 3.1 in Table 1. The focal plane is
203 cooled to 75 K by the miniature cryocooler (Q). A thermal strap (P) couples the cold finger of the
204 cryocooler to the detector focal plane. Cryogenic cooling is required to reduce thermal noise in the
205 detectors. The light entering the SABER telescope is also chopped (K) to create an AC signal that
206 can be synchronously detected and thereby readily distinguished from the large infrared DC
207 background of the instrument. More detail on the instrument design and operation is given below.

208 The Johns Hopkins University Applied Physics Laboratory (APL) designed and fabricated
209 the TIMED spacecraft. Figure 3 shows the SABER instrument installed in the TIMED spacecraft
210 at APL. The extent of the front surface of SABER can be identified by the planar white surfaces,
211 which are SABER's radiators. The darker oval surface in the smaller, white-surfaced radiator is
212 the covered entrance aperture to the instrument.



213

214 **Figure 3.** The SABER instrument installed in the TIMED spacecraft.

215

216 ***2.1 Detailed Instrument Description***

217 A photograph of the assembled SABER instrument before it was covered by multilayer

218 insulation (MLI) is shown in Figure 4. The instrument view is rotated 90 degrees to the left from

219 the view in Figure 2. MLI blanketing details are described later in Section 2.1.1, SABER Purge

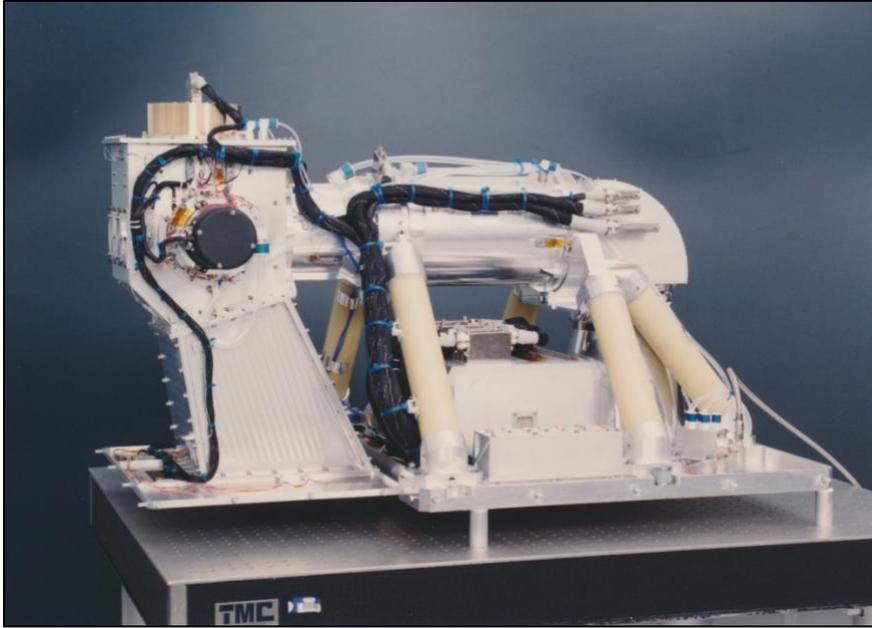
220 and Vent System. The long G-10 fiberglass legs (the tan colored struts in Figure 4) thermally

221 isolate the optics (contained in the cylindrical-shaped tube) from the SABER/spacecraft interface

222 plate. Thermal, envelope, mass, and moment of inertia parameter values are summarized in Table

223 6 in Section 3.4. Component parameter values and descriptions are given in the component section

224 of this paper (Section 4).

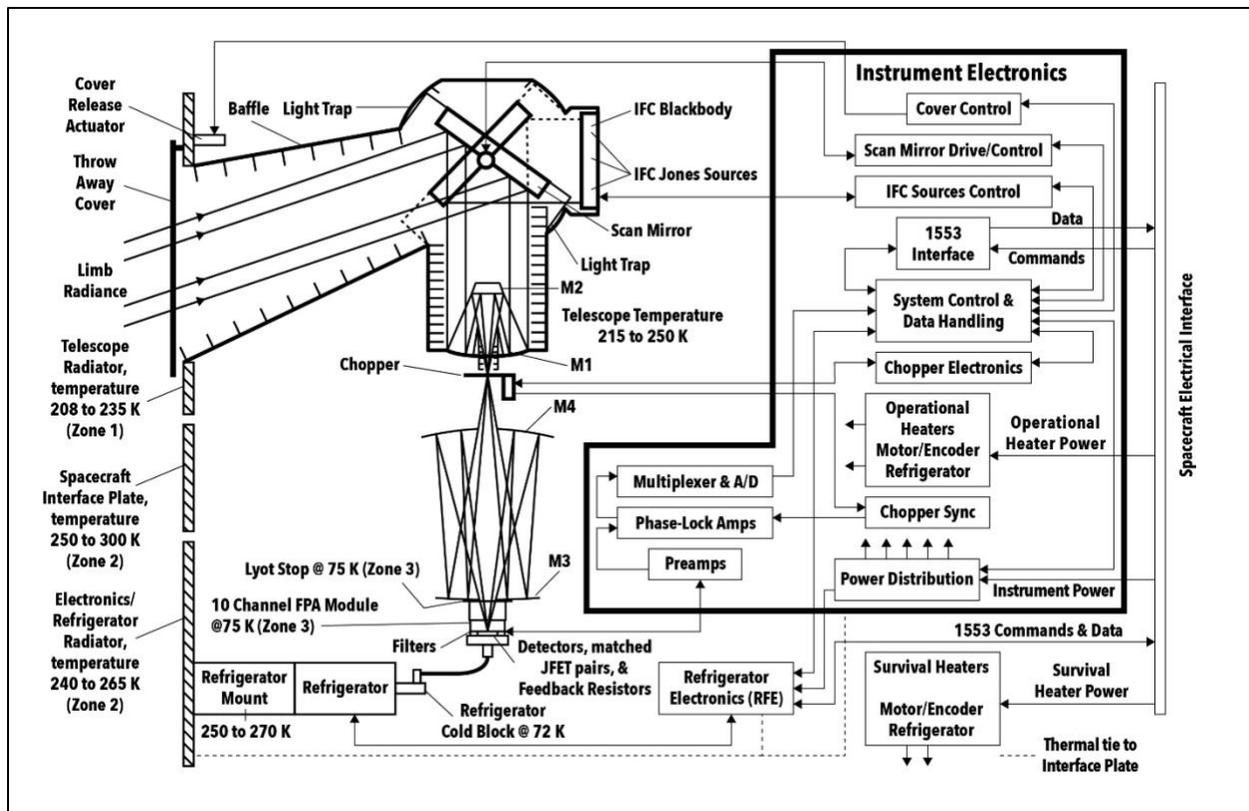


225

226 **Figure 4.** Assembled SABER instrument before it was covered with multi-layer insulation.

227

228 A functional block diagram of the SABER instrument is shown in Figure 5. This block
229 diagram (also see Figure 2) shows that incoming radiance from the Earth limb is focused on to a
230 mechanical chopper (operating at a frequency of 1000 Hz) by mirrors M1 and M2, which form a
231 Ritchey-Chrétien telescope, and are then reimaged by a clamshell re-imager consisting of mirrors
232 M3 and M4 onto a focal plane assembly (FPA). This FPA contains a Lyot stop, an array of 10
233 detectors covered by an array of 10 passband filters, 10 matched junction-gate field effect transistor
234 (JFET) pairs, and 10 feedback resistors. The JFET pairs and feedback resistors form the input
235 stages of 10 transimpedance amplifiers (TIA). The TIA input stages are connected by low thermal
236 conductance stainless steel wires to the remaining TIA components which are located inside the
237 electronics box.



238

239 **Figure 5.** SABER functional block diagram.

240

241 The chopped signals measured by the 10 detectors are amplified by the 10 TIA
 242 preamplifiers and then demodulated by 10 phase lock amplifiers and multiplexed into a single
 243 analog to digital (A/D) converter that converts the analog signals to digital signals. These digital
 244 signals are transferred to the spacecraft by means of a 1553 interface. A one-axis scan mirror with
 245 the axis of rotation on the mirror surface to prevent optical beam walk, scans the field of view
 246 (FOV) from hard Earth to cold space (approximately 400 km tangent altitude) and periodically
 247 points the FOV at an in-flight calibrator (IFC), which consists of a full-aperture blackbody and
 248 three partial aperture Jones sources.

249 The SABER instrument has three separate temperature zones as shown in Figure 5: Zone
 250 1 which includes the telescope zone at temperature of 208 K to 250 K; Zone 2 which includes the

251 electronics/refrigerator zone at a temperature of 240 K to 270 K; and Zone 3, the FPA zone at a
252 temperature of 75 K. Zone 1 consists of the telescope radiator, the telescope, the scan mirror, the
253 IFC, the optical baffles, and the chopper mechanism. The telescope radiator is used when looking
254 at deep space past the Earth limb and cools the telescope to reduce photon noise, reduces the heat
255 load on the refrigerator, and minimizes the temperature of the full-aperture blackbody. The
256 spacecraft undergoes a yaw maneuver every 60 days so that the telescope radiator and aperture,
257 which are parallel to the orbit plane, are never exposed to direct sunlight. The telescope is thermally
258 isolated from the warmer SABER support structure and the TIMED spacecraft bus by thermal
259 blankets and telescope support struts (as shown in Figure 4).

260 Zone 2 consists of the electronics/refrigerator radiator, all electronics except the electronics
261 inside the FPA, the refrigerator, and the TIMED spacecraft interface plate. The electronics box is
262 bolted directly to the backside of the electronics/refrigerator radiator. Because the reject
263 temperature of the refrigerator plays an important role in the overall cooling capacity of the
264 refrigerator, precise control of the refrigerator reject temperature was needed. The SABER control
265 electronics can operate under a wide range of temperatures without significantly affecting their
266 performance.

267 Zone 3 consists of the FPA housing, a Lyot stop, 10 optical bandpass filters, 10 detectors,
268 10 matched JFET pairs, and 10 feedback resistors. The FPA is cooled through a flexible heat strap
269 connected to a cryogenic pulse-tube refrigerator. The operation of the SABER instrument is
270 described later in this section, and additional descriptions of its components are given in the
271 component section of this paper.

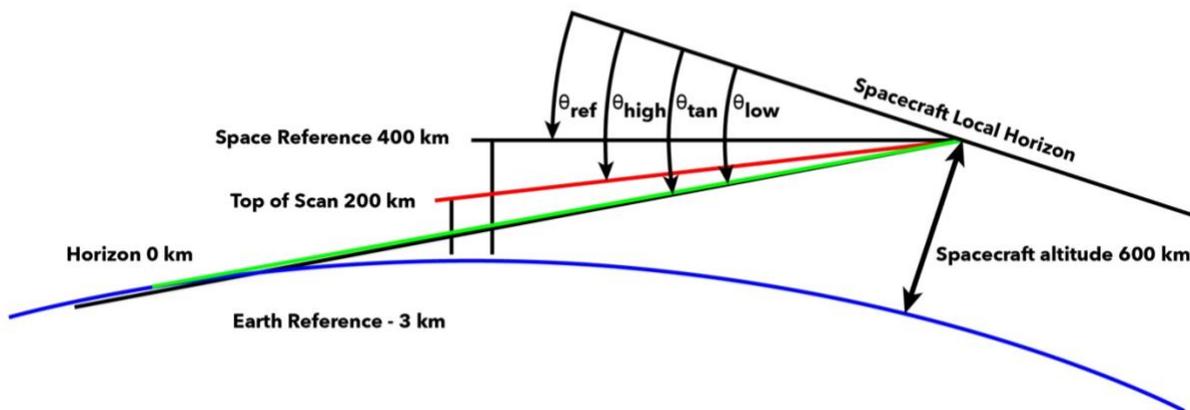
272 The SABER telescope consists of an ejectable aperture cover with a wax-actuator cover
273 release mechanism, a baffle, an optics radiator, a spacecraft interface plate that also serves as the

274 electronics and cryogenic cooler radiator, a single-axis scan mirror, a light trap around the scan
 275 mirror, a Ritchey-Chrétien telescope consisting of mirrors M1 and M2, a chopper, a two-mirror
 276 clamshell re-imager consisting of mirrors M3 and M4, an FPA, a power distribution and
 277 conditioning box, a cover controller, a scan mirror driver, an IFC, and an IFC temperature
 278 controller, chopper electronics, operational heaters, survival heaters, and a scan mirror angle
 279 encoder.

280 The scan mirror continually scans the SABER FOV from hard Earth to deep space and
 281 back. Periodically, the scan mirror also points the FOV at the IFC. M1 and M2 focus the Earth
 282 limb radiance onto a 10-aperture chopper which amplitude modulates the radiance. M3 and M4
 283 reimage the modulated light onto 10 discrete detectors in the FPA. The FPA consists of a Lyot
 284 stop, an array of 10 filters, an array of 10 detectors, and an array of JFET pairs and feedback
 285 resistor-capacitor combinations that determine the spectral parameters of the SABER instrument.

286 The SABER instantaneous field of view (IFOV) scan angles are defined with respect to the
 287 spacecraft local horizon as shown schematically in Figure 6.

288



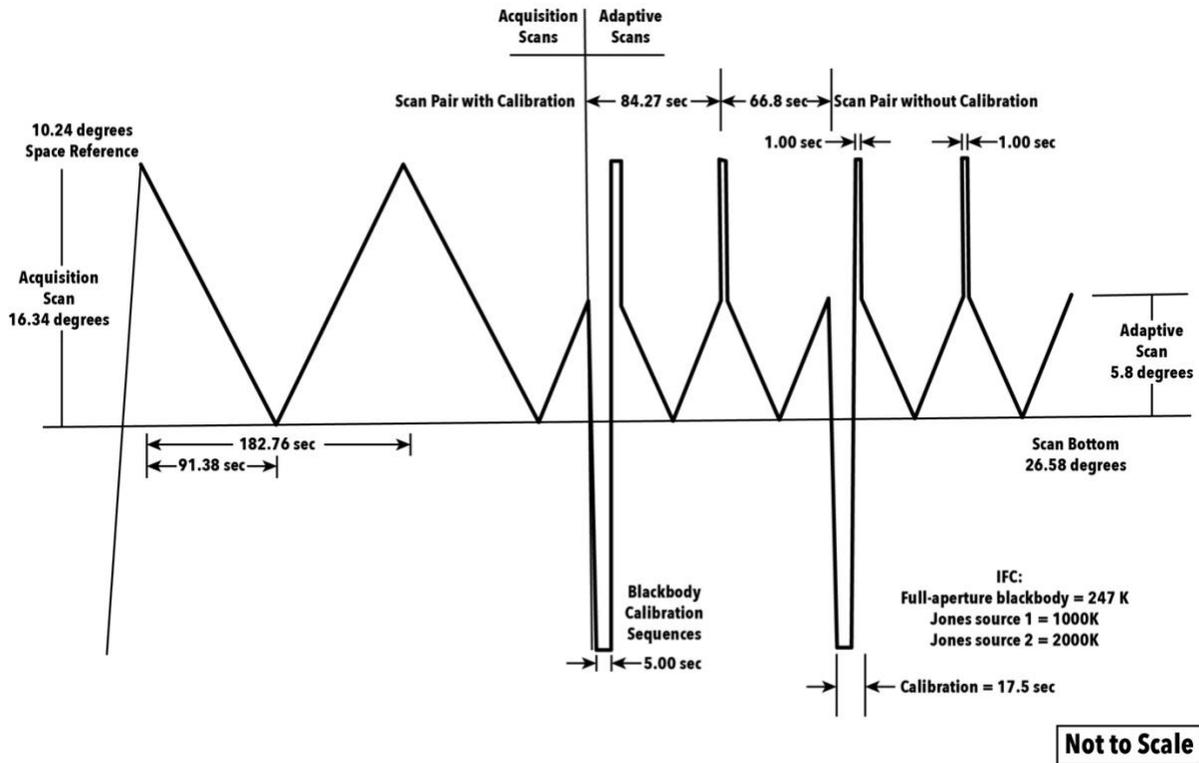
289

290 **Figure 6.** Schematic sketch defining SABER scan angles relative to the spacecraft local horizon.

291 The SABER instrument Earth limb scan sequence is shown schematically in Figure 7
292 where the acquisition scan profile is on the left side of the figure and the adaptive scan is on the
293 right. The acquisition mode is used to locate the altitude of the CO₂ (W) layer, and only used when
294 the scanner is transitioned from the safe-hold position to scanning. The adaptive scan mode is used
295 to make scientific measurements of atmospheric emissions in the 10 SABER spectral bands. Both
296 the acquisition scan and the adaptive scan accommodate worst-case spacecraft altitude and attitude
297 variations over the mission life. The limb scan sequence is very similar to that used by the Limb
298 Infrared Monitor of the Stratosphere (LIMS) instrument that flew in the late 1970s on the Nimbus
299 VII spacecraft.

300 The width of the acquisition scan is 16.34 degrees because the bottom of the acquisition
301 scan is 26.58 degrees with respect to the spacecraft local horizon and the top is 10.24 degrees. The
302 width of the adaptive scan is 5.8 degrees because the bottom of the adaptive scan is 26.58 degrees
303 and top of the adaptive scan is 20.78 degrees. For every other adaptive scan, the scanner slews
304 rapidly to the space reference and dwells for 10 sample periods before slewing back to the top of
305 the adaptive scan. During adaptive scanning the offset is corrected based on the wide-channel CO₂
306 (W) data. The adaptive scan rate provides five samples in each 2 km vertical interval at 60 km
307 tangent height. Periodically, the scan mirror points at the IFC for 17.5 seconds.

308

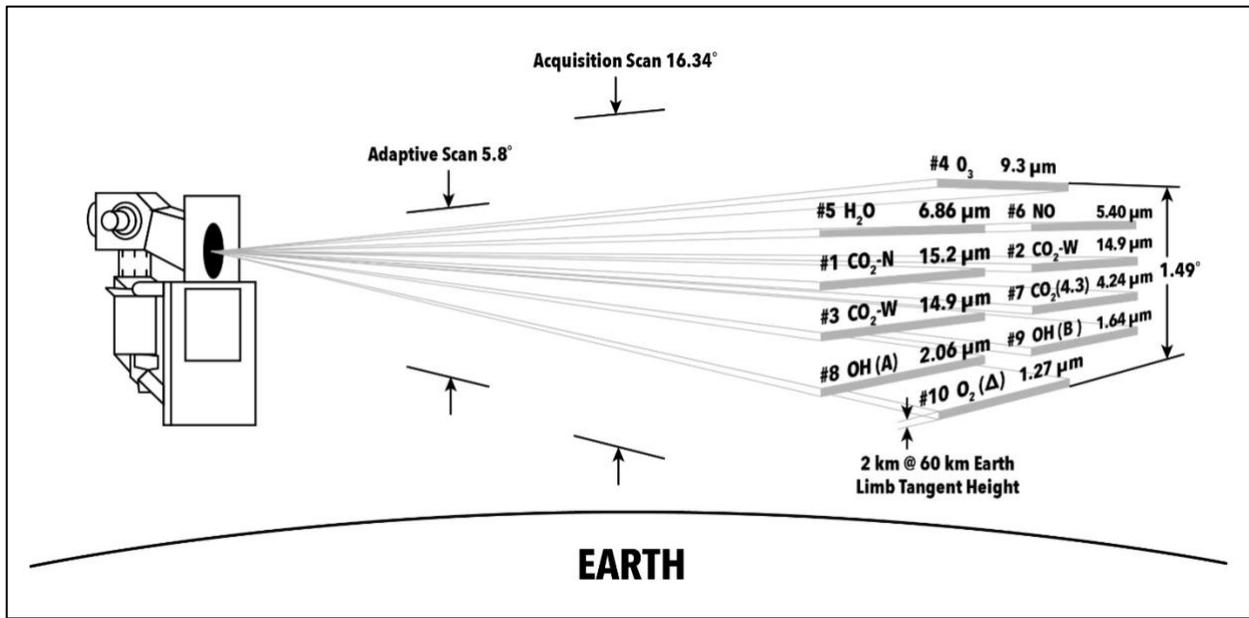


309

310 **Figure 7.** SABER Earth limb scan sequence.

311

312 The relative locations of the 10 IFOVs on the atmosphere are shown in Figure 8. Each
 313 IFOV is nominally 2 km wide at an Earth limb tangent height of 60km and its length is as long as
 314 the optical system would allow to maximize the signal. The scan mirror translates these IFOVs up
 315 and down through the atmosphere using the acquisition or adaptive scan modes.



316

317 **Figure 8.** IFOVs of the 10 SABER detectors on the atmosphere.

318

319 2.1.1 SABER Purge and Vent System

320

321

322

323

324

325

326

327

328

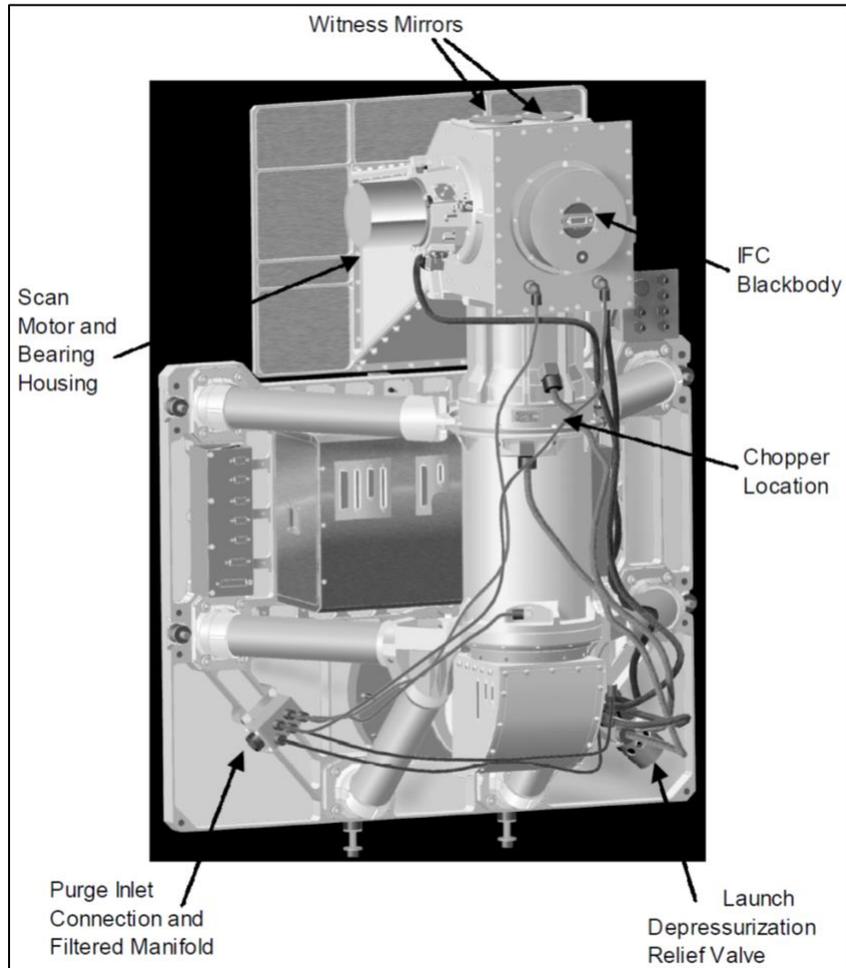
329

330

331

To reduce vulnerability to water outgassing and to control particulate redistribution and contamination within the detector assembly (which is not hermetically sealed) SABER was designed with an optimized purge and vent system (*Dyer et al., 2002*) as shown in Figure 9. The purge system maintained the cleanliness and optical quality for those times when SABER was not being operated under or stored in vacuum. To make the purge system effective, dry nitrogen gas needs to be distributed uniformly into critical compartments and the escape paths must be minimized so that a slight positive pressure (4-6 Torr) can be maintained at a reasonable flow rate. This was accomplished using a purge manifold that distributed dry nitrogen to five locations: two ports in the fore-optics and scanner compartment, and one port each for the re-imager compartment, the pulse tube/thermal link compartment, and the detector. The telescope purge lines were 1/8" Teflon tubing and the FPA used 1/16" tubing to restrict the gas flow to < 3% of the total purge (nominally 0.5 standard cubic feet per meter (SCFM) at 4 psi delivery pressure). The purge

332 manifold includes a 5- μ m particle filter and for each purge fitting, the telescope uses a sintered
333 metal gas snubber filter disk to provide additional filtering and eliminate stray light leaks. Once
334 installed, the purge system operated continuously whenever the sensor was not under vacuum.



335

336 **Figure 9.** The SABER instrument purge and vent system.

337

338 To minimize the risk from rapid launch depressurization, a very low pressure/high flow
339 relief valve was designed and tested to maintain positive pressure during purge operations and
340 control the SABER instrument depressurization vent paths during launch. The spring load on the
341 valve was adjustable to allow 0.2-0.7 scfm flow rates at 3-6 Torr pressure differential during

342 purging. However, when exposed to rapid decreases in pressure, the relief valve would open and
343 allow the SABER instrument volume to completely evacuate within 60 seconds.

344 The vent port fittings attached to the telescope used a black labyrinth that would not impede
345 gas flow but still minimized the entry of stray light. The vents were strategically located in critical
346 areas of the telescope: 1) the scanner motor and encoder which each had a vent on its body so that
347 gas flow and particulates (from the bearings) would be directed away from the optics; 2) a vent
348 port located on each side of the small chopper apertures reduced the flow of gas across the chopper
349 and reduced the possibility of damage; and 3) a vent port located on the thermal link compartment
350 directed particles from the MLI away from the detector and optics. The vent ports connected to
351 the relief valve with 3/8” Teflon tubing. The entire back of the SABER sensor was completely
352 enclosed in a 40-layer MLI blanket with a 5-mil outer layer to immunize the sensor from the
353 spacecraft thermal and outgassing environment. Since the vent valve was inside the MLI “tent”,
354 purging under this configuration created a local N₂ environment outside of the telescope housing
355 as well as inside. Furthermore, the isolation afforded by the SABER thermal mechanical and
356 optical design eliminated the need for spacecraft bakeout requirements.

357 **3. SABER Instrument Level Parameters**

358 This section describes instrument level parameters including radiometric, optical, and
359 electrical in addition to SABER instrument performance.

360 Table 1 presents the spectral parameter values for each of the 10 SABER infrared channels.
361 SABER is a filter radiometer with each channel having a unique filter over its detector. The filter
362 passes infrared radiation with a defined spectral region that optimizes the ability to derive
363 temperature and constituent concentrations from the infrared radiance measurements. The filters
364 are characterized by ‘cut-on’ and ‘cut-off’ wavelengths that define the observed spectral interval.

365 There is further a central wavelength of this spectral region defined by the cut-on and cut-off. The
366 transmission of each filter is typically normalized to 1.0 at the maximum transmittance value. From
367 this, wavelengths at which the transmittance is 5% (relative to the peak transmittance) on either
368 size of the passband center is specified. The spectral specification is given in both wavelength
369 (μm) and reciprocal wavelength or wavenumbers (cm^{-1}). It is critical that the spectral filter pass
370 radiation only within the specified bandpass. For this reason, an out of band rejection ratio is
371 defined for each filter. In Table 1 the “W” and “N” on the CO_2 channels refer to ‘wide’ and
372 ‘narrow’ in the sense of the spectral width of the channels. There are also two channels observing
373 emission from the hydroxyl (OH) radical labeled “A” and “B”. Other channels measure infrared
374 radiation from ozone (O_3), water vapor (H_2O), nitric oxide (NO). Channel 7 measures infrared
375 radiation from CO_2 near 4.3 micrometers.

376

377 **Table 1.** SABER instrument level spectral parameter values.

Channel No	Species	Passband Center		5% Relative Cut-On		5% Relative Cut-Off		Out-Of-Band Rejection Ratio
		(cm^{-1})	(μm)	(cm^{-1})	(μm)	(cm^{-1})	(μm)	
1	CO_2 (N)	674	14.837	698	14.327	649	15.408	< 5E-04
2	CO_2 (W)	672	14.881	764	13.089	581	17.212	< 1E-04
3	CO_2 (W)	672	14.881	763	13.106	580	17.241	< 1E-04
4	O_3	1080	9.259	1146	8.726	1013	9.872	< 3E-04
5	H_2O	1468	6.812	1567	6.382	1369	7.305	< 1E-04
6	NO	1903	5.255	1944	5.144	1862	5.371	< 1E-04
7	CO_2	2348	4.259	2392	4.181	2203	4.539	< 1E-04
8	OH (A)	4830	2.07	5151	1.941	4509	2.218	< 1E-04
9	OH (B)	6078	1.645	6414	1.559	5741	1.742	< 1E-04
10	O_2	7836	1.276	7969	1.255	7704	1.298	< 1E-04

378

379 **3.1 SABER Noise Equivalent Radiance and Dynamic Range**

380 The SABER instrument level radiometric parameter values are shown in Table 2. The NER
381 values in this table were measured during ground calibration. The other parameter values are final
382 design values. The NER is the radiance value that results in a signal-to-noise ratio of unity. The

383 dynamic range is the ratio of the maximum radiance to the NER. The maximum radiance is the
 384 ratio of the radiance of a 300 K blackbody (indicated in the fourth column of Table 2) to the NER
 385 for channels 1 through 7. For channels 8 through 10 it is the ratio of the modeled Earth and
 386 atmosphere radiance at a tangent height of -3 km to the NER.

387 The definitions of NER, dynamic range, and maximum signal are given in the footnotes to
 388 Table 2. Three programable amplifiers with adjustable DC offsets follow each of the ten phase-
 389 look amplifiers to make it possible to cover the required dynamic gains with a 12-bit analog to
 390 digital converter (ADC). The gains of these amplifiers that achieve the required dynamic ranges
 391 for each of ten channels are given in Table 2. The maximum radiance values for channels 1 through
 392 7 are the radiance values of a 300K blackbody, and the maximum radiance values for channels 8
 393 through 10 are modeled radiance values from the earth and atmosphere at a tangent height of -3
 394 km.

395
 396 **Table 2.** Instrument level radiometric parameter values.

Channel		^{1,2} NER (W/m ² sr ⁻¹)	300 K Radiance (W/m ² sr ⁻¹)	Modeled Earth & Atmosphere Radiance (W/m ² sr ⁻¹)	³ Dynamic Range (N/A)	Programable Amplifier Gains			Gain Trip Points in ADC counts	
#	Species					High (V/V)	Medium (V/V)	Low (N/A)	High (N)	Low (N)
1	CO ₂ (N)	2.45E-04	5.63E+00	2.70E+00	2.3E+04	21.1	21.1	1.0	4080	174
2	CO ₂ (W)	2.84E-04	2.44E+01	9.98E+00	8.6E+04	60.0	7.7	1.0	4080	470
3	CO ₂ (W)	3.32E-04	2.44E+01	9.98E+00	7.3E+04	68.6	8.3	1.0	4080	442
4	O ₃	3.96E-05	9.49E+00	5.67E+00	2.4E+05	183.4	13.6	1.0	4080	269
5	H ₂ O	2.36E-05	5.48E+00	4.96E-01	2.3E+05	152.5	12.2	1.0	4080	294
6	NO	1.48E-06	3.63E-01	2.03E+00	2.5E+05	210.1	11.0	1.0	4080	192
7	CO ₂	8.02E-07	1.48E-01	1.60E-02	1.8E+05	76.8	8.9	1.0	4080	413
8	OH (A)	1.28E-06	7.75E-05	2.48E+00	1.9E+06	1107.5	29.5	1.0	4080	110
9	OH (B)	3.33E-06	4.48E-07	4.68E+00	1.4E+06	1080.4	33.1	1.0	4080	111
10	O ₂	2.49E-06	4.64E-11	2.15E+00	8.7E+05	376.3	19.6	1.0	4080	187

397 ¹Noise Equivalent Radiance (NER) is radiance value that results in a Signal-to-Noise Ratio (SNR) of unity.

398 ²NER values are from the ground calibration.

399 ³Dynamic Range = (Maximum Radiance)/NER

400 where (Maximum Radiance) equal radiance of 300 K blackbody for channels 1 thru 7,
 401 and modeled radiance of earth and atmosphere at a tangent height of -3 km for channels 8 thru 10.
 402

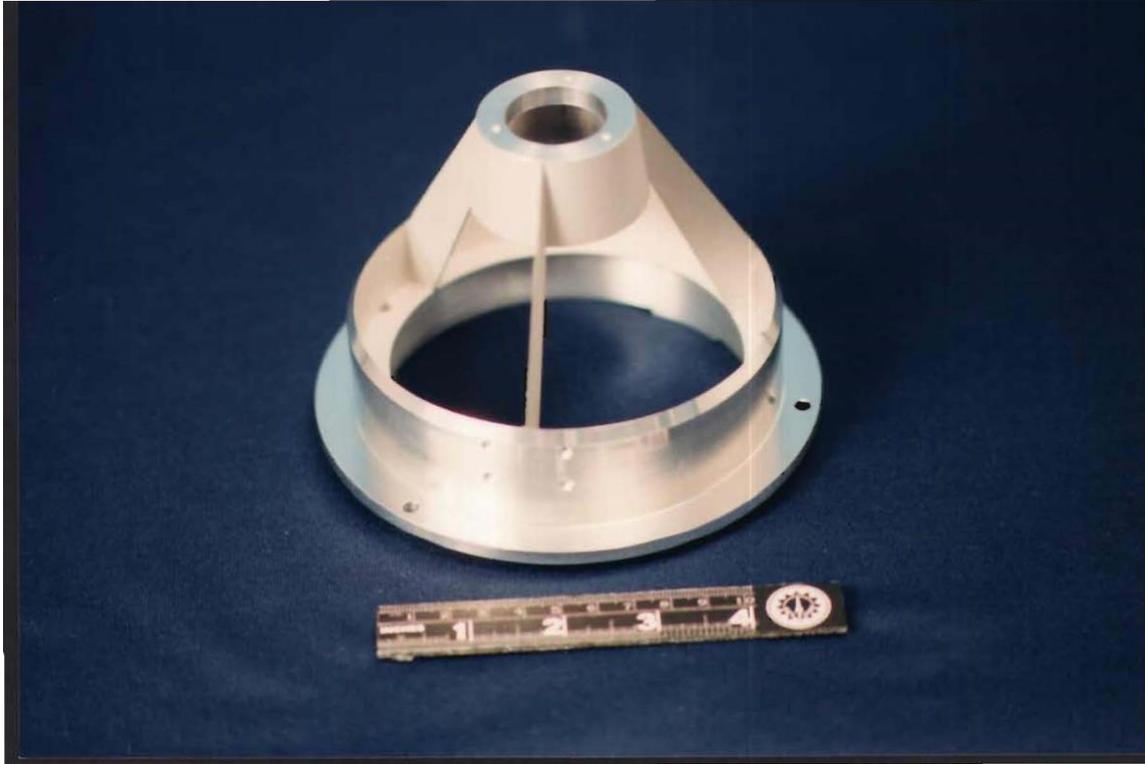
403 **3.2 SABER Optical Parameters**

404 The instrument level optical parameters with the same values for all channels are shown in
 405 Table 3.

406
 407 **Table 3.** SABER instrument level optical parameters that have the same value for all channels.

Parameter	Value	Units
Spacecraft Orbit Altitude at launch	625 ± 25	km
Effective Focal Length (EFFL)	200	mm
Entrance Pupil Diameter	98	mm
Central Obscuration Diameter	54	mm
Number of Secondary mirror struts	3	N/A
Total strut obscurations area	3.219	cm ²
Entrance Pupil Area	49,309	cm ²
Solid Angle Ω	0.115	
Chopper Modulation Factor	0.446	N/A
Chopping Frequency	1000	Hz
Limb Scan Mirror Jitter (1σ)	1.5	arcsec
Limb Vertical Sampling Interval	0.38	km
FOV Scan Velocity	0.179	deg/sec
Acquisition Scan	16.34	deg
Adaptive Scan Range	5.8	deg
Optical Clear Fields of View	± 30 Horizontal, 25 Top, 55 Bottom	deg
Thermal Clear field of View	180 in all direction	deg
Ground Dry Nitrogen Purge Rate	0.5 (At 4 psi delivery pressure)	SCFM

408
 409 The image of the entrance aperture, the central obscuration, and the secondary mirror
 410 assembly define the optical beam that reaches the detector. The image at the Lyot stop of the outer
 411 edge of the entrance aperture, which is located right in front of the primary mirror, defines the
 412 outer edge of the optical beam which is focused on the detectors. The image of the secondary
 413 mirror baffle at the Lyot stop defines the inner limit of this optical beam. The secondary mirror
 414 which includes the secondary mirror and the secondary mirror baffle, is supported by a 3-vane (3-
 415 leg) spider (Figure 10).



416

417 **Figure 10.** Secondary mirror support and baffle.

418

419 The solid angle, Ω , of the collected light beam at the detector is defined by the half angle
 420 at the detector of the image of the outer aperture edge (θ_1), and half angle at detector of inner
 421 aperture edge image (θ_2), and the fraction of the exit pupil annulus formed by the images of the
 422 outer aperture and inner aperture not obstructed by spider vanes (τ_a). The value of the solid angle
 423 for all channels is the same. The solid angle was computed using the follow equation:

$$424 \quad \Omega = \tau_a \pi (\sin \theta_1^2 - \sin \theta_2^2) \quad (1)$$

425 Its value, as shown in Table 3, is 0.115.

426 The chopper modulation factor 0.446 is the same for all detectors and is very close to the
 427 perfect square wave modulation factor, 0.4502. Image smear is minimized by the small value of
 428 limb scan jitter. The scanning parameters are illustrated in the limb scan sequence in Figure 8
 429 above. The clear optical field of view on the spacecraft is specified to prevent glints from getting

430 into the entrance aperture. The radiators clear field of view maximize the efficiency of the
 431 radiators. The SABER instrument was purged up to launch with dry gaseous nitrogen to minimize
 432 contamination from water and particles. The purge system was shown previously in Figure 9.

433 The SABER instrument level optical parameters whose values are specific to each channel
 434 are shown in Table 4. The vertical instantaneous IFOVs seen by each detector at a tangent viewing
 435 height of 60 km are approximately 2 km. The detector areas, A_d , vary slightly from detector to
 436 detector due mainly to differences in the detector's vertical dimensions. The optical throughput,
 437 $A_d\Omega$, quantifies the extent of the optical beam on each detector. The parameter τ_o is the total fraction
 438 of light transmitted to the detector by the product of the reflections at the five mirrors and the
 439 transmittance of the filters.

440

441 **Table 4.** SABER instrument level optical parameters whose values are specific to each channel.

Channel		IFOV @ 60 km Tangent Height	Optical Throughput ($A_d\Omega$)	Transmittance (τ_o)
No	Species	(km)	(cm^2sr)	(N/A)
1	CO ₂ (N)	1.68	2.92E-04	0.673
2	CO ₂ (W)	1.59	2.91E-04	0.820
3	CO ₂ (W)	1.49	2.92E-04	0.820
4	O ₃	1.97	3.38E-04	0.796
5	H ₂ O	1.73	3.41E-04	0.782
6	NO	1.97	3.39E-04	0.641
7	CO ₂	2.12	3.37E-04	0.638
8	OH (A)	1.97	3.44E-04	0.776
9	OH (B)	1.97	3.44E-04	0.757
10	O ₂	1.97	3.41E-04	0.549

442

443 3.3 SABER Electrical Parameters

444 The SABER instrument electrical parameters are listed in Table 5. The integration time is
 445 the observation time per measurement. The signal to noise ratio (SNR) increases as the square root
 446 of the integration time. The SABER instrument bandwidth is determined by 10 low-pass, 4-pole

447 Butterworth filters located in the signal processing string right after the phase-lock amplifiers. The
 448 noise equivalent bandwidth (NEBW) is the bandwidth of an ideal square bandwidth that the same
 449 noise as the true bandwidth. NEBW was calculated using the following equation.

$$450 \quad NEBW = \left(\frac{\pi}{2}\right)^{\frac{1}{8}} f_{3dB} = 4.687 Hz \quad (2)$$

451 where

$$452 \quad f_{3dB} = 4.430 Hz \quad (3)$$

453 is the 3dB bandwidth of a 4-pole Butterworth filter. The total data rate sent down to the earth is
 454 extremely small; it is only 3969.7 bits/sec. The required instrument power depends chiefly on how
 455 much sunlight is incident on the radiators. The amount of sunlight on the radiators is determined
 456 by the β angle, the angle between the solar vector and its projection on the orbit plane.

457

458 **Table 5.** SABER instrument level electrical parameter values.

Parameter	Value	Units
Integration time	0.110	s
Noise Equivalent Bandwidth (Δf)	4.545 (1/[2x0.110 sec])	Hz
Electrical 3dB Bandwidth	4.430 (4 pole Butterworth response)	Hz
Data Sample Rate	22.727 (2.5 x Nyquist sample rate of 9.09 Hz)	Hz
Data Collection Rate	3969.7	bits/s
Instrument Power	52.64 Cold Case $\beta=90^\circ$, 61.04 Cold Case $\beta=0^\circ$ by test	Watts
Operational Heater Power	27.16 Cold Case $\beta=90^\circ$, 0.0 Cold Case $\beta=0^\circ$ by test	Watts
Operational Power	79.80 Cold Case $\beta=90^\circ$, 61.04 Cold Case $\beta=0^\circ$ by test	Watts
Survival Heater Power	48.60 Cold Case $\beta=90^\circ$, 0.0 $\beta=0^\circ$ by test	Watts
Total Peak Power	120.3 (operational cold case $\beta=90^\circ$)	Watts
Supply Voltage	24 to 35, nominal 28	Volts
Electronic Box Size	441 (width) by 262 (height) by 192 (depth)	mm
Electronic Box Mass (Electronics Box including TRW cryocooler electronics)	7.9 \pm 0.3	kg
Motherboard and Cards Mass	6.1 \pm 0.3	kg
Electronic Box Dissipated Power	29.0 cold case, 29.7 hot case	watts
Maximum Junction Operating Temperature	< 373	K
Minimum Expected Operating Temperature	248	K
ΔT between Radiator and Most Distant Component	\leq 75	K
Electronic Box Interface Temperature (on orbit)	245 to 262	K
Radiation Hardness (Total Dose, no latch-up, recoverable SEU)	5	krad
Reliability	17,500	hrs

459

460

461 3.4 SABER Temperature, Mass, Size, Cleanliness, and Mission Life Parameters

462 The SABER instrument level temperature, mass, size, cleanliness, and mission life
463 parameter values are shown in Table 6.

464

465 **Table 6.** SABER instrument level temperature, mass, size, cleanliness, and mission lifetime
466 parameter values.

Parameter	Value	Units
Telescope Radiator Temperatures	209 Extreme Cold Case, 228 Extreme Hot Case	K
Telescope Average Temperatures	214 Extreme Cold Case, 237 Extreme Hot Case	K
Electronics and Cryocooler Radiator Temperature	244 Extreme Cold Case, 263 Extreme Hot Case	K
Refrigerator Mount Temperature	260 Extreme Cold Case, 278 Extreme Hot Case	K
FPA Temperature	75	K
Envelope	797 Width x 676 Depth x 1049 Height	mm
Mass	74.58 Launch Configuration, 74.07 Cover Deployed	kg
SABER Coordinate System Origin (SCSO) Location	At scan shaft center	N/A
Center of Mass about SCSO	0.43 X, 17.37 Y, 38.00 Z Launch 0.43 X, 17.26 Y, 38.24 Z Cover Deployed	cm
Moments of Inertia about SCSO at Launch	$I_{xx}=20.92, I_{yy}=18.43, I_{zz}=6.218, I_{xy}=0.168, I_{yz}=6.606, I_{xz}=0.390$	kg m ²
Moments of Inertia about SCSO after Cover Deployed	$I_{xx}=20.83, I_{yy}=18.41, I_{zz}=6.140, I_{xy}=0.168, I_{yz}=6.581, I_{xz}=0.390$	kg m ²
Loads Environment	15.5 Max of Launch & Testing Loads (Driven by Sine Burst Test)	g
Vibration Environment	8.5 (TIMED proto-flight level Environmental Spec for 72 kg mass)	g rms
Minimum Frequency Stiffness	49.13 Hz (thrust axis, 40.31 Hz (x axis), 42.04 Hz (y axis))	Hz
Exterior Cleanliness Level	750	N/A
Mission Life	2 required, but SABER still taking excellent data after 21	years

467

468 3.5 SABER Stray Light Parameters

469 SABER is an instrument that measures infrared emission from the atmosphere by viewing
470 the limb of the Earth. As shown previously in Figure 1, SABER limb radiance measurements cover
471 a large dynamic range of several orders of magnitude, depending on channel. This fact places very
472 stringent requirements on the stray light rejection properties of the SABER instrument. As noted
473 above, the IFOV of SABER is 2 km. Light entering the instrument and falling on the detector from

474 outside this IFOV is considered stray light. The entrance aperture of SABER is illuminated by the
475 entire atmosphere below the tangent point. Because of the rapid increase of radiance with
476 decreasing tangent altitude, SABER's optical system must be capable of rejecting several orders
477 of magnitude of radiance emitted within just a few degrees below the observed tangent height. For
478 the CO₂ (W) channel (which is used to derive temperature) shown previously in Figure 1, 1% of
479 the radiance from 45 km tangent height is equal to the radiance at 80 km tangent height. For
480 SABER and all thermal emission limb sounders, rejection of off-axis (out of field) radiation is
481 paramount.

482 SABER's optical system was designed specifically to have extremely high rejection of off-
483 axis light. Initial analysis of SABER's stray light performance is reported by *Stauder et al.* (1995).
484 During the development of the instrument, a stray light analysis was performed using a non-
485 sequential ray tracing Zemax model of SABER and an SDL software program to compute the
486 Normalized Detector Irradiance (NDI). NDI is a fundamental measure of an instrument's
487 sensitivity to off axis stray light. It is the ratio of irradiance reaching the detector to that incident
488 on the entrance port to the instrument, as a function of off-axis angle, and is computed using the
489 following equation:

$$490 \quad NDI(\theta) = \frac{\text{Detector Irradiance}(\theta)}{\text{Port Irradiance}(\theta)} \quad (4)$$

491 where θ is the angle that the source beam makes with the telescope baffle centerline. The point
492 source is assumed to be at an infinite distance and is represented by a collimated ray bundle that
493 fills the baffle entrance aperture. The computed instrument NDI values for each SABER channel
494 at specified tangent heights are illustrated in Table 7 and plotted in Figure 11. For the example of
495 the CO₂ (W) channel given above, the 45 km tangent height is approximately 1 degree in angle

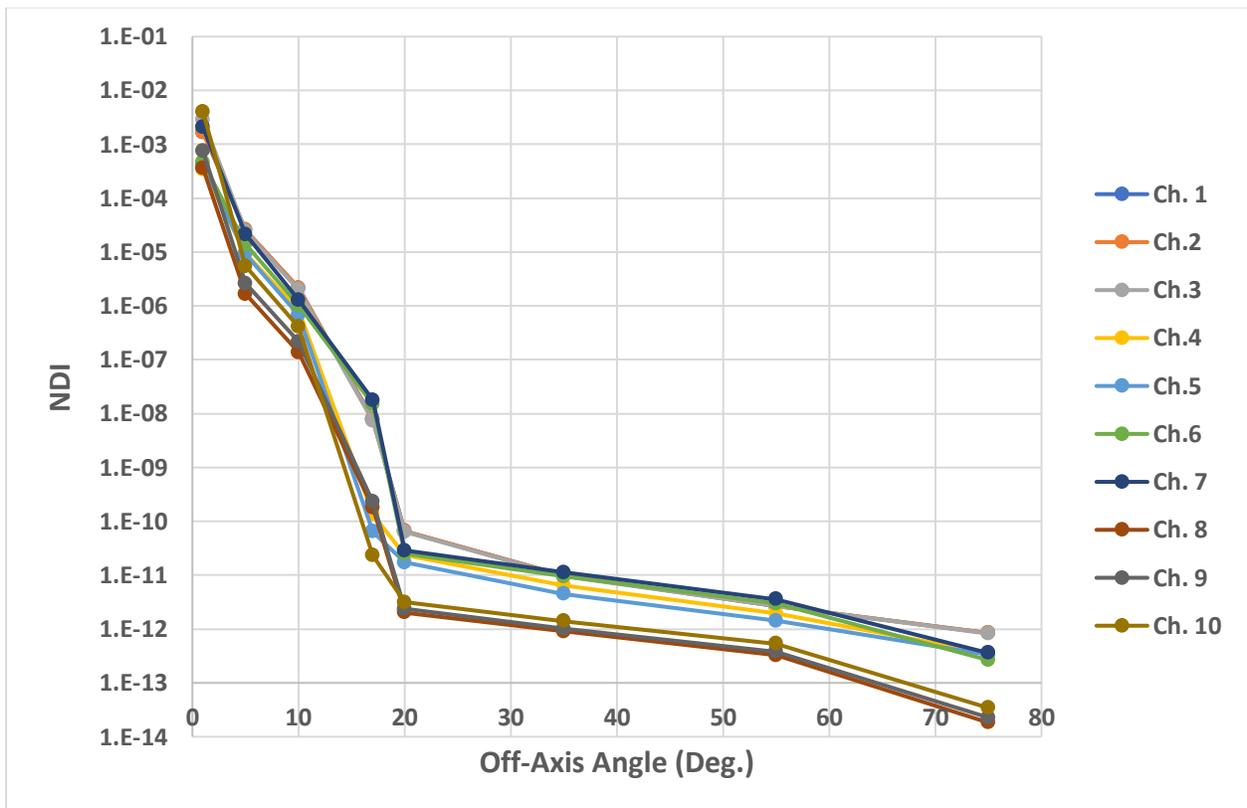
496 below the 80 km tangent height from SABER's orbit altitude. Table 7 shows an NDI of 0.17% for
 497 the CO₂(W) channel at 1 degree, illustrating the exceptional off-axis rejection of the instrument.

498

499 **Table 7.** SABER instrument NDI as a function of off-axis angle (q) in degrees.

#	Channel	Center Wave-length (mm)	NER (W/[cm ² sr])	Tangent Height h _{tan} (km)	NDI							
					Off-Axis Angle (degrees)							
	Species				1	5	10	17	20	35	55	75
1	CO ₂ (N)	14.837	2.45E-04	70	1.7E-03	2.6E-05	2.2E-06	7.9E-09	6.7E-11	9.8E-12	2.7E-12	8.4E-13
2	CO ₂ (W)	14.881	2.84E-04	70	1.7E-03	2.6E-05	2.2E-06	7.8E-09	6.7E-11	9.8E-12	2.7E-12	8.4E-13
3	CO ₂ (W)	14.881	3.32E-04	70	2.8E-03	2.4E-05	2.0E-06	7.3E-09	6.4E-11	9.5E-12	2.7E-12	8.2E-13
4	O ₃	9.259	3.96E-05	70	3.4E-04	9.5E-06	8.6E-07	1.4E-10	2.3E-11	6.5E-12	2.0E-12	3.6E-13
5	H ₂ O	6.812	2.36E-05	70	4.3E-04	9.0E-06	6.7E-07	6.4E-11	1.7E-11	4.5E-12	1.4E-12	3.3E-13
6	NO	5.255	1.48E-06	100	4.7E-04	1.4E-05	1.0E-06	1.5E-08	2.5E-11	9.4E-12	3.0E-12	2.7E-13
7	CO ₂	4.259	8.02E-07	80	2.1E-03	2.1E-05	1.3E-06	1.8E-08	2.9E-11	1.1E-11	3.6E-12	3.6E-13
8	OH (A)	2.07	1.28E-06	87	3.6E-04	1.7E-06	1.4E-07	1.8E-10	2.0E-12	9.0E-13	3.2E-13	1.8E-14
9	OH (B)	1.645	3.33E-06	87	7.4E-04	2.6E-06	2.2E-07	2.3E-10	2.4E-12	1.0E-12	3.8E-13	2.3E-14
10	O ₂	1.276	2.49E-06	70	4.0E-03	5.4E-06	4.1E-07	2.3E-11	3.1E-12	1.4E-12	5.3E-13	3.4E-14

500



501

502 **Figure 11.** SABER instrument NDI plots versus off-axis angle.

503

504 The product of the NDI curve and the radiance from the Earth and atmosphere is integrated
505 over all angles in the hemisphere of angles looking out from SABER to compute the Non-Rejected
506 Radiance (NRR) at various tangent heights for each SABER channel. Two figures of merit are
507 developed to assess SABER’s off-axis rejection performance. The first is the ratio of the NRR to
508 NER reported earlier in Table 2 and listed in Table 8 in the column labeled (NRR/NER). This
509 column demonstrates that the SABER non-rejected radiance at the indicated tangent altitudes is
510 substantially less than the instrument noise, sometimes by several orders of magnitude.

511 The second figure of merit is the ratio of the limb radiance at a given tangent height to the
512 NRR. This ratio, listed in the right-most column of Table 8, is the “signal-to-stray-light ratio.” As
513 seen in Table 8, it ranges from 120 to over 628,000 depending on channel and tangent height. Both
514 figures of merit indicate that SABER has excellent stray light rejection ability. Operational
515 experience and the SABER data quality as reflected in more than 2200 peer-reviewed publications
516 confirms this excellent optical performance.

517

518 **Table 8.** SABER non-rejected radiance metrics

Channel		Center Wave-length	NER	Tangent Height h_{tan}	NRR	NRR/NER	Radiance (h_{tan})	Radiance(h_{tan}) /NRR
#	Species	(mm)	($Wm^{-2}sr^{-1}$)	(km)	($Wm^{-2}sr^{-1}$)	(N/A)	($Wm^{-2}sr^{-1}$)	(N/A)
1	CO ₂ (N)	14.837	2.45E-04	70	5.113E-05	2.090E-01	2.326E-02	455
2	CO ₂ (W)	14.881	2.84E-04	70	1.854E-04	6.530E-01	3.562E-02	192
3	CO ₂ (W)	14.881	3.32E-04	70	2.980E-04	8.980E-01	3.562E-02	120
4	O ₃	9.259	3.96E-05	70	1.318E-09	3.327E-05	2.645E-04	200784
5	H ₂ O	6.812	2.36E-05	70	1.204E-09	5.104E-05	2.638E-04	219001
6	NO	5.255	1.48E-06	100	1.117E-07	7.600E-02	1.093E-04	978
7	CO ₂	4.259	8.02E-07	80	2.880E-07	3.590E-01	2.294E-04	796
8	OH (A)	2.07	1.28E-06	87	9.169E-10	7.163E-04	5.766E-04	628895
9	OH (B)	1.645	3.60E-08	87	4.159E-09	1.160E-01	8.541E-04	205335
10	O ₂	1.276	2.49E-06	70	1.481E-08	5.948E-03	4.095E-04	27649

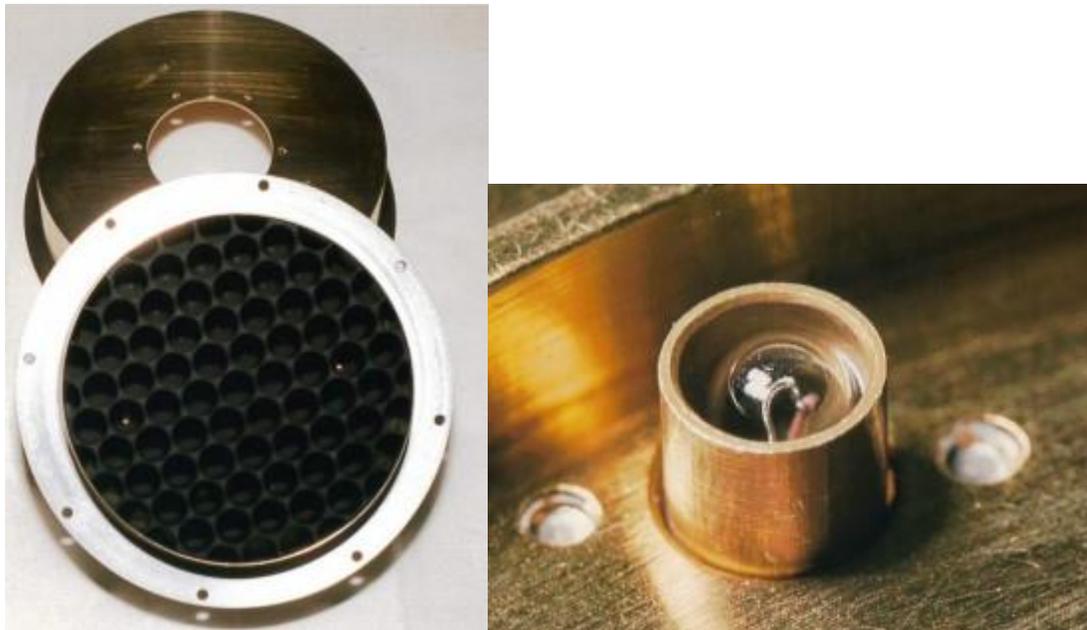
519

520 **4. Major Components of the SABER Instrument**

521 **4.1 SABER In-Flight Calibrator**

522 The SABER IFC consists of a full-aperture black body and three partial-aperture Jones
523 sources (items E and F in Figure 2). The full-aperture body is used for the long-wavelength
524 channels numbered 1 through 6, and the Jones source calibrators are used for the short-wavelength
525 channels numbered 7 through 10. The full-aperture blackbody is shown in Figure 12(a) and one of
526 the three tungsten-filament Jones sources, before it is embedded in the full-aperture blackbody, is
527 shown in Figure 12(b). After embedding, two of the three Jones sources can be seen as white glints
528 in Figure 12(a).

529



530

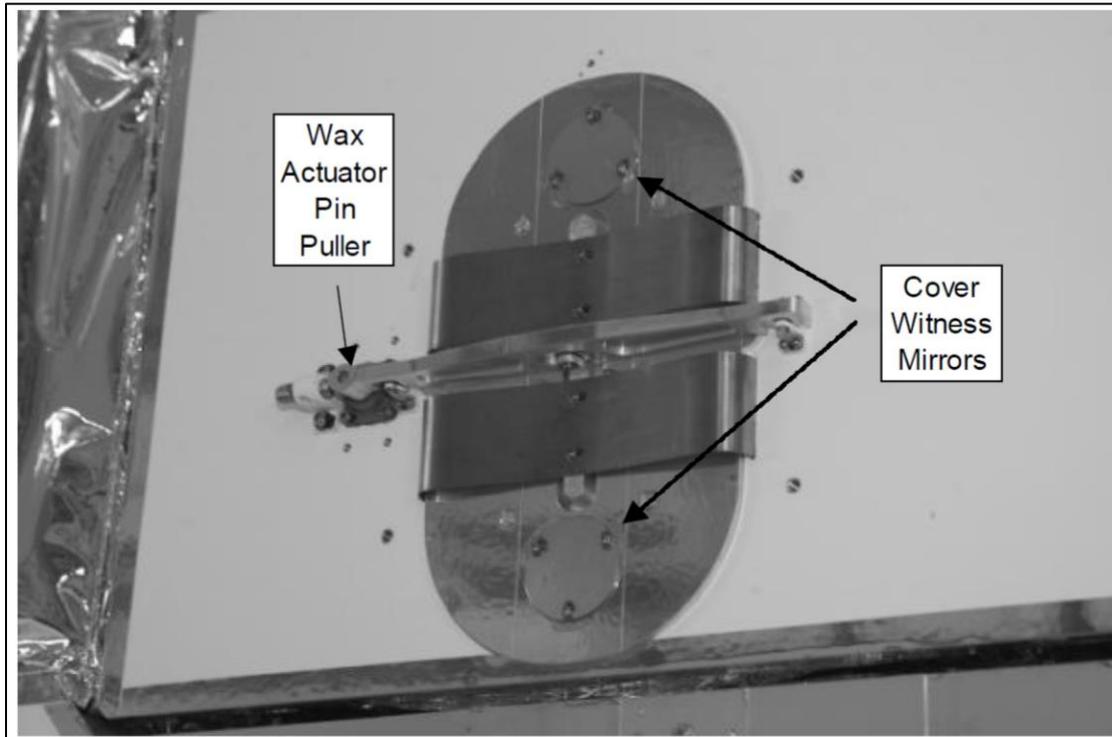
531 **Figure 12.** (a, left image) Full aperture blackbody, (b, right image) one of three tungsten-filament

532 Jones sources before being embedded in the full-aperture blackbody.

533

534 **4.2 Entrance Aperture Cover**

535 The SABER entrance aperture cover, its wax actuator pin puller, and two removable
536 witness mirror covers are shown in Figure 13. These witness mirrors, which were removed and
537 replaced by covers before launch, were used to monitor contamination during SABER integration,
538 testing, storage, shipping, and TIMED launch preparations. The SABER aperture cover protected
539 the inside of the SABER instrument from contamination during SABER integration, testing,
540 storage, shipping, launch preparations, and during the maximum outgassing period at the start of
541 the mission. The SABER cover was ejected by a spring after the wax actuator pulled the retaining
542 pin. At the time of when TIMED was launched, it was still acceptable to eject instrument covers
543 without consideration of the implications for space debris. The entrance aperture cover is the item
544 labeled X in Figure 2.

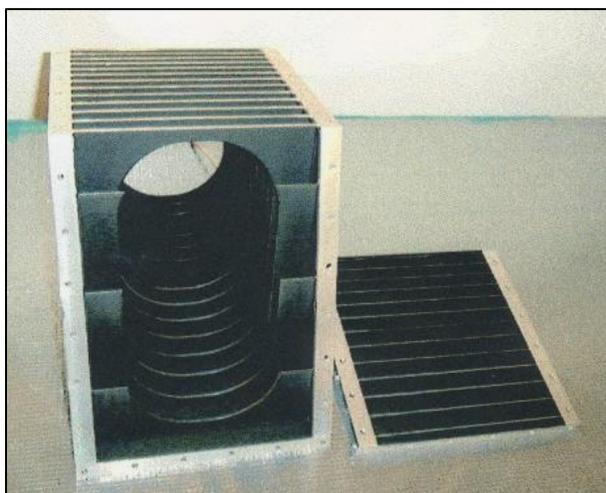


545
546 **Figure 13.** SABER aperture cover with its wax actuator pin puller and removable witness mirrors.

547

548 **4.3 Fore-Optics Baffle Assemblies**

549 The fore-optics baffle assembly, which provides baffling before the scan mirror, is shown
550 in Figure 14 with its top removed. The baffle assembly is indicated as item B in Figure 2, located
551 in the optical train between the optics radiator and the scan mirror. After painting, the baffle blades
552 and baffle tips were wiped clean to minimize the baffle tip radius and hence minimize scattered
553 light from the baffle tips. The number of baffle blades was made just large enough to satisfy the
554 two-bounce rule for light in the baffle cavities.



555
556 **Figure 14.** Fore-optics baffle assembly.

557
558 The baffle surrounding the Ritchey-Chrétien telescope is a cylindrical baffle with its
559 entrance port at an angle to prevent it from blocking needed rays on their way to the scan mirror.
560 This baffle is shown below in Figure 15 and surrounds mirrors M1 and M2 (Items H and J in
561 Figure 2). A schematic drawing of this baffle can be seen in Figure 5, which also shows a schematic
562 sketch of the fore-optics baffle.

563



564

565 **Figure 15.** SABER main baffle assembly.

566

567 ***4.4 Encoder/Motor Assembly***

568 The encoder/motor/bearing assembly is the cylindrical assembly mounted on the side of

569 the baffle identified previously in Figure 9. This assembly is the black cylinder in the Figure 4

570 photograph. The parameter values of the encoder/motor assembly are given in Table 9. The

571 encoder/motor/bearing assembly rotates the scan mirror and measures the scan mirror angle. The

572 center of rotation is on the front surface of the scan mirror on the vertical centerline of this mirror.

573 The ion-coated bearing lubrication is one of the most critical parameters because this mirror must

574 rotate smoothly and easily when the bearing temperature is in the 215 to 250 K range. Periodically,

575 the mirror is rotated past its operational limits to push any lubrication build up on the bearing races

576 past the operational rotation limits. One of the most important pointing parameters for mapping
 577 the radiance versus tangent height is the encoder accuracy of 25 μ radians rms (5.2 arc seconds).

578

579 **Table 9.** Encoder motor assembly parameter values.

Parameter	Value	Units
Total Rotation Travel (stop to stop)	84.4	deg
Maximum Rotor Rotational Rate	14.3	deg/sec
Pointing Accuracy	6	arcsec
Pointing Precision	0.088	deg
Moment of Inertia (Includes inertia of mirror and shaft)	6112	kg mm ²
Bearing Lubrication	Ion-coated lead	N/A
Mass	1.85	Kg
Friction Torque (Cogging and Bearing)	0.86	kg-mm
Motor Type	Brushless 3 phase DC	N/A
Number of Motor Poles	12	N/A
Motor Commutation	Hall Effect Sensors	N/A
Motor DC Resistance @ 25°C	10.8 \pm 10%	ohms
Motor Inductance	4.5 \pm 30%	mH
Voltage @ 32.55 oz-in (25°C)	25.0 nominal	volts
Torque Sensitivity	15.1 \pm 20%	kg-mm/amp
Back EMF	0.148 \pm 10%	volts/rad/sec
Motor Winding Isolation	> 100, < 100	M Ω , pF
Motor Constant	4.623	kg-mm/vw
Encoder Outputs	Quadrature w/zero ref	N/A
Encoder Cycles per Channel/Revolution	262,144 (2 ¹⁸)	N/A
Encoder Accuracy (over 360° rotation)	25	μ rad rms
Signal Minimum Level (RS422)	2	volts pk to pk
Motor Power	0.7	watts
Encoder Power	2.1	watts
Non-Operating Temperature Range	208 to 333	K
Operating Temperature Range	215 to 250	K
Δ T at Encoder Mount to Baffle	5	K
Design Life Total Scan Cycles	3.8E6 (3 years)	N/A

580

581 **4.5 Mirrors**

582 The SABER optical system has five mirrors: the scan mirror; mirrors M1 and M2, which
 583 constitute a Ritchey-Chrétien telescope that focuses the input light on the chopper; and M3 and
 584 M4, which constitute a clamshell re-imager that reimages the chopper holes onto the filters and
 585 detectors. The locations of these mirrors in the SABER optical train can be seen in Figure 2 as
 586 items J, H, M, and L, respectively.

587 All the mirrors have aluminum mirror substrates that were thermal cycled between room
588 temperature and liquid nitrogen temperatures to minimize residue internal stress. The mirror
589 substrates have a 6:1 diameter to thickness aspect ratio and lapped, flexible three-point mounting
590 pads to minimize reflected wavefront error. The aluminum substrates were diamond turned and
591 polished to near final optical figure, then the front and back of the mirror substrates were coated
592 with electroless nickel. The thickness of the nickel on the back surface was slightly less than on
593 the front surface so that the thicknesses of the front and back nickel coating were nearly equal after
594 polishing. Only a narrow strip near the front of each mirror is nickel coated so that mirror
595 deformation due to hoop stress when the mirror is coated is minimized. This thin strip can be seen
596 on the edges of the primary mirror and the tertiary mirror later in this document in Figure 16
597 (Section 4.5.1) and Figure 23 (Section 4.9), respectively. After nickel coating, the mirrors were
598 super polished to their final optical figure. Super polishing minimizes the bi-directional reflectance
599 distribution (BRDF) function and hence minimizes reflected stray light. Finally, the mirrors were
600 coated with a very thin layer of gold to maximize reflectance at the SABER passband wavelengths
601 and minimize thermal emissions.

602 4.5.1 Scan Mirror

603 The scan mirror parameters are listed in Table 10 and indicated as item C in Figure 2. The
604 most important scan mirror parameters are the BRDF and peak-to-valley surface error. The BRDF
605 of the scan mirror is exceptional good; that is, it is small and decreases rapidly with increasing
606 angle from the reflecting surface normal. This was achieved by applying an electroless nickel
607 coating over an aluminum substrate. The nickel coating allowed super-polishing of the mirror to a
608 rms surface roughness of approximately 10 Angstroms, which results in these good BRDF values.
609 After super-polishing, this mirror was coated with electrolytic gold to produce the high reflectance

610 value given in this table for the total infrared spectral region measured. Electrolytic gold scatters
611 less than vacuum deposited gold. The peak-to-valley surface error at the 215 to 250 K operational
612 temperature of the scan mirror was achieved by making the ratio of the maximum length across
613 the reflected surface of the mirror to the thickness equal to 6 to 1 and by also nickel coating the
614 back surface of the scan mirror with same thickness of nickel. This relatively large aspect ratio
615 incurs a mass penalty. Nickel coating the front and back surface with the same thickness of nickel
616 and making the coating as thin as possible minimizes mirror bending at the cryogenic temperatures.
617 The distance the nickel coating extends around the mirror edge is minimized to minimize hoop
618 stress when this mirror is cooled. All the SABER mirrors are fabricated using the procedures
619 described above for the scan mirror.

620

621 **Table 10.** Scan mirror parameter values.

Parameter	Value	Units
Material	Gold on 0.003" thick nickel on aluminum substrate	N/A
Optical Surface Figure	Plane	N/A
Size	157.256 by 110.752 oval	mm
Peak-to-Valley Surface Error @ 300 K	0.197	633 nm waves
BRDF	2.10E-3/ $\theta^{2.54}$ @ 10.6 μm 1.12E-2/ $\theta^{2.88}$ @ 13.39 μm 6.14E-4/ $\theta^{2.06}$ @ 1.2 μm	steradian ⁻¹
ΔT across mirror	≤ 2	K
Reflectance	0.98	NA
Mass (measured)	0.86	kg
Mass of Scan Mirror Shaft Assembly (includes light trap, mirror, mirror counterbalance)	2.13	kg

622

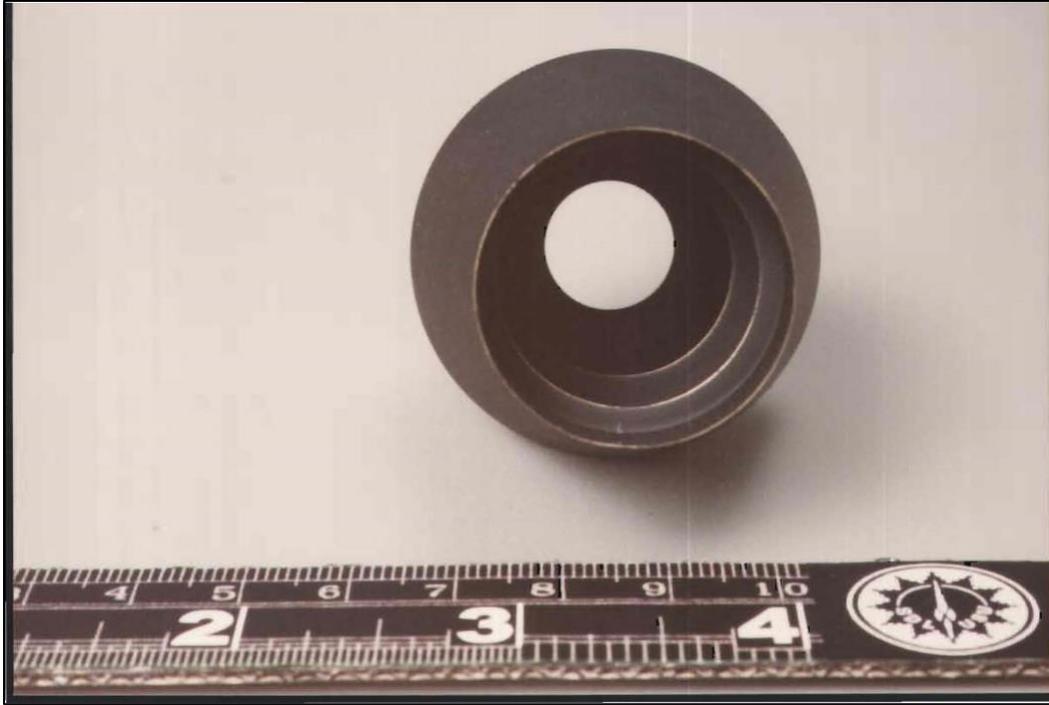
623 4.5.2 Primary Mirror

624 The primary mirror, M1, is shown in Figure 16. The features that appear to be on the surface
625 in this photo are images of the area surrounding the mirror when this photo was taken. The hole in
626 the center of this mirror is to mount the primary inner conical baffle that is shown in Figure 17.

627 After painting and while the paint was still wet, the baffle blade edges were wiped clean of paint
628 as can be seen in Figure 17. This wiping procedure prevents the large amount of scattered light
629 that would result from a ball of paint on the baffle edge. Primary mirror parameter values are given
630 in Table 11. The primary mirror is fabricated using the same procedure described above for the
631 scan mirror to minimize its BRDF and its peak-to-valley surface error. The Ritchey-Chrétien
632 telescope, which consists of M1 and M2, corrects both spherical aberration and coma by using
633 hyperbolic mirrors for both the primary and secondary mirrors. Its primary mirror optical surface
634 is slightly flatter than the parabolic primary mirror used in the classical Cassegrain telescope. The
635 secondary mirror of the classical Cassegrain telescope is hyperbolic like the Ritchey-Chrétien
636 telescope.



637
638 **Figure 16.** SABER Primary mirror M1.
639



640

641 **Figure 17.** Primary mirror inner-conic baffle.

642

643 **Table 11.** Primary mirror parameter values

Parameter	Value	Units
Material	Gold on 0.003" thick nickel on aluminum substrate	N/A
Radius of Curvature	225.000 concave	mm
Conic Constant	-1.15149 hyperboloid	mm
Outer Diameter	106	mm
Inner Diameter	48.006	mm
Peak-to-Valley Surface Error @ 300 K	0.23	633 nm waves
BRDF (θ is the angle off specular expressed in degrees)	$9.73E-5/\theta^{1.83}$ @ 10.6 μm $2.42E-3/\theta^{2.88}$ @ 3.39 μm $2.42E-3/\theta^{2.03}$ @ 1.2 μm	steradian ⁻¹
Reflectance	0.98	N/A
ΔT across mirror	≤ 2	K
Mass	0.39	kg

644

645 4.5.3 Secondary Mirror, Secondary-Mirror Spider, and Secondary-Mirror Baffle

646 A photograph of the secondary-mirror support was shown previously in Figure 10. The
 647 secondary mirror support and baffle were fabricated as one piece using a plunge electrical
 648 discharge machining (EDM) technique. The relatively rough EDM finish made good diffuse

649 surfaces. The support vanes are beveled in the direction of the rays so only the baffle edges nearest
650 the primary mirror can be seen at the Lyot stop. The Ritchey-Chrétien telescope, whose optical
651 elements are the primary and secondary mirrors, was focused by means of a planar shim between
652 the top of the second spider and the secondary mirror mounting plate.

653 The assembly procedure to install the secondary mirror was to first lay a nominal thickness
654 ring shim on the top of the support and then insert secondary mirror mounting feet through the
655 hole in the top of the support, bolt these feet to a mounting plate, and finally bolt the mounting
656 plate to the top of the support. The focus location and image quality of the M1-M2 pair was
657 checked interferometrically. The thickness of the shim and the decenter of the secondary mirror
658 relative to the primary mirror was iterated until the focus location and image quality requirements
659 were satisfactory.

660 Secondary mirror parameters are given in Table 12. The secondary mirror is fabricated
661 using the same procedures described above for the scan mirror to minimize its BRDF and its
662 peak-to-valley surface error. The optical surface of this mirror has a hyperbolic shape that is
663 defined by the values of the conic constant and the radius of curvature. The hyperbolic shape
664 slightly flattens the edge of the mirror surface compared to a spherical shape. The secondary mirror
665 is more hyperbolic than the primary mirror. The secondary mirror together with the primary mirror
666 form a Ritchey-Chretien telescope, which has zero spherical aberration and zero coma.

667

668

669

670

671

672 **Table 12.** Secondary mirror parameter values

Parameter	Value	Units
Material	Gold on 0.003" thick nickel on aluminum substrate	N/A
Radius of Curvature	120.000 convex	mm
Conic Constant	-6.62063 hyperboloid	mm
Outer Diameter	40.5	mm
Peak-to-Valley Surface Error @ 300 K	0.0817	633 nm waves
BRDF (θ is the angle off specular expressed in degrees)	2.44E-3/ $\theta^{3.01}$ @ 10.6 μm 1.86E-3/ $\theta^{2.881}$ @ 3.39 μm 6.14E-4/ $\theta^{2.06}$ @ 1.2 μm	steradian ⁻¹
Reflectance	0.98	N/A
Mass (measured)	0.38	kg

673

674 4.5.4 Tertiary and Quaternary Mirrors

675 The tertiary and quaternary mirror pair form a clamshell re-imager optical system. After
676 light passes through the chopper, it passes through a hole in the quaternary mirror and is reflected
677 by the tertiary mirror back to the quaternary mirror that then reflects it to the FPA. The parameter
678 values of the tertiary and quaternary mirror or given in Table 13 and Table 14, respectively. The
679 tertiary mirror is fabricated using than same procedures described above for the scan mirror to
680 minimize its BRDF and its peak-to-valley surface error. The tertiary and quaternary mirrors form
681 a clamshell re-imaging system. Together they re-image the focus of the Ritchey-Chretien, which
682 is located at the tuning fork chopper, at the detector. The tertiary mirror is hyperbolic with an
683 optical surface flatter than a sphere and even a parabola. The quaternary mirror is an oblate
684 ellipsoid with the ellipse foci on opposite sides of the optical axis which makes the optical surface
685 look like a doorknob or the top of a spinning planet.

686

687

688

689

690 **Table 13.** Tertiary mirror parameter values.

Parameter	Value	Units
Material	Gold on 0.003" thick nickel on aluminum substrate	N/A
Radius of Curvature	1050.000 concave	mm
Conic Constant	-6.62063 hyperboloid	mm
Outer Diameter	127.000	mm
Inner Diameter	23.978	mm
Peak-to-Valley Surface Error @ 300 K	0.153	633 nm waves
Reflectance	0.98	N/A
Mass (measured)	0.76	kg

691

692 **Table 14.** Quaternary mirror parameter values.

Parameter	Value	Units
Material	Gold on 0.003" thick nickel on aluminum substrate	N/A
Radius of Curvature	384.407 concave	mm
Conic Constant	0.3910 oblate ellipsoid	mm
Outer Diameter	165.000	mm
Inner Diameter	37.998	mm
Peak-to-Valley Surface Error @ 300 K	0.231	633 nm waves
Reflectance	0.98	N/A
Mass (measured)	1.55	kg

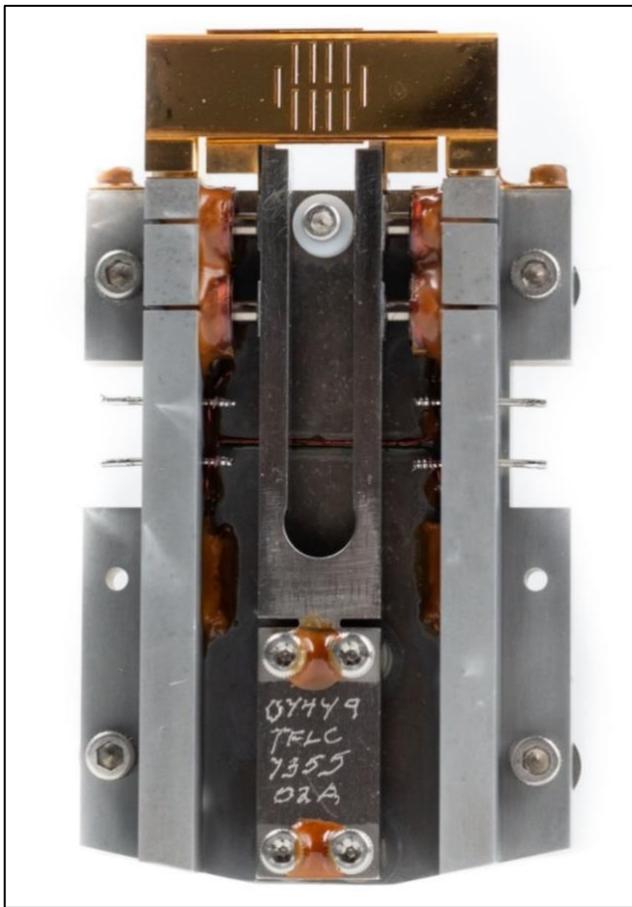
693

694 **4.6 SABER Optical Chopper**

695 The SABER optical chopper (Figure 18) is located at the focus of the Ritchey-Chrétien
696 telescope. Its position in the optical train is shown as item K of Figure 2. The SABER chopper is
697 a “picket-fence” chopper, with two shutters that in principle function like two translating parallel
698 picket fences. This design amplitude modulates the light in each of the 10 IFOVs while requiring
699 only small mechanical translations of the chopper blades. This small motion maximizes chopper
700 reliability and makes it possible to chop at 1000 Hz, which is well above the 1/f noise knee of the
701 photoconductive HgCdTe detectors used for channel numbers 1 through 5. The SABER chopper
702 was made by TFR Laboratories Inc, which is now out of business. This chopper provides a nearly
703 square wave chopping of the light collected on each of SABER’s 10 detectors. The chopper
704 efficiency is 0.446, which is very close to the maximum possible value of 0.4502 for a true square-
705 wave chop.

706 As can be seen in Figure 18, each of the chopped areas is half open at rest. The chopper
707 blades are gold coated so they have an infrared emissivity < 0.05 , which minimizes thermal
708 emissions from the chopper shutters. The chopper has one set of coils to drive the chopper and one
709 set of coils to produce the reference for synchronous demodulation. The chopper operating
710 temperature is 215 K for the cold case and 240 K for the hot case. The chopper produces a
711 mechanical disturbance of 0.002 lb-ft and its measured mass is 0.095 kg.

712



713

714 **Figure 18.** The SABER "picket-fence" chopper

715

716 **4.7 SABER Focal Plane Array (FPA)**

717 The SABER FPA consists of a detector array and filter array located inside the detector
 718 assembly and a Lyot mounted on top of the detector assembly. The filter assembly was designed
 719 and fabricated by Optical Coating Laboratory (OCLI; now VIAVI Solutions Inc.). The detector
 720 array was designed and fabricated by E&G Optoelectronics (now Teledyne Judson Technologies;
 721 TJT). SDL designed and fabricated the Lyot stop. The focal plane assembly is indicated as item O
 722 in Figure 2.

723 Photoconductive (PC) detectors are used for the long-wavelength detector channels
 724 (channels 1 through 5) and photovoltaic (PV) for the short-wavelength detector channels. Table
 725 15 and Table 16 show the parameter values for the PC and PV detectors, respectively. All
 726 parameter values are at the 1000 Hz SABER chopping frequency. D* is the detector specific
 727 detectivity.

728 **Table 15.** SABER photoconductive (PC) detector parameter values.

Channel		Detector Material	Detector Resistance	Detector Resistance	Bias Current	Bias Power	Noise	Average Responsivity	Average D*	
Number	Species		@ 296K	@ 75K	(mA)	(mW)	@ 1kHz	(V/W)	@ 1kHz	
				(Ω)	(Ω)	(mA)	(mW)	(μV/rtHz)	(V/W)	(cm ² √Hz/W)
1	CO ₂ (N)	HgCdTe	249	699	1.5	1.6	12.07	1.9E+04	7.53E+10	
2	CO ₂ (W)	HgCdTe	233	606	1.5	1.4	11.57	1.4E+04	5.76E+10	
3	CO ₂ (W)	HgCdTe	269	681	1.5	1.5	13.1	1.5E+04	5.44E+10	
4	O ₃	HgCdTe	530	1274	1.0	1.0	7.46	1.4E+05	9.19E+11	
5	H ₂ O	HgCdTe	1209	2563	1.0	1.0	9.56	1.2E+05	6.50E+11	

729

730 **Table 16.** SABER photovoltaic (PV) detector parameter values.

Channel		Detector Material	Feedback Resistance	JFET Pair Bias Power	Noise	Average Responsivity	Average D*
Number	Species		(Ω)	(mW)	@ 1kHz	(A/W)	@ 1kHz
				(mW)	(μV/rtHz)	(A/W)	(cm ² √Hz/W)
6	NO	InSb	6.28E+07	3.2	0.69	3.69	1.8E+13
7	CO ₂	InSb	7.10E+08	3.3	0.44	2.89	2.5E+14
8	OH (A)	InSb	1.49E+08	3.3	0.22	1.74	6.3E+13
9	OH (B)	InSb	9.06E+07	3.3	0.55	1.06	9.3E+12
10	O ₂	InGaAs	9.56E+07	3.3	0.21	0.92	2.3E+13

731

732 The spectral parameters of the SABER filters are given in Table 17. These filters are
 733 mounted on top of the detectors and provide the spectral isolation needed to provide radiances in
 734 well-defined spectral intervals. Accurate specification and characterization of the filters is essential
 735 as they and the detectors provide the overall instrument spectral response. The spectral response
 736 functions are used in the process of deriving all SABER data products. Component level testing
 737 and analysis of the SABER spectral response is described by *Hansen et al.*, (2003).

738 **Table 17.** SABER optical filter parameter values.

Channel Number	Cut-On			Cut-Off			Avg. Transmission Between HPP (%)	Avg. Out-of-Band Transmission (%)	Long Wavelength Blocking Limit (μm)
	5% Absolute		Slope	5% Absolute		Slope			
	(cm^{-1})	(μm)	(%)	(cm^{-1})	(μm)	(%)			
1	698.2	14.323	1.27	648.2	15.427	1.13	74.4	≤ 0.05	22.4
2	760.2	13.154	1.61	577.45	17.319	1.77	90.7	≤ 0.03	24.4
3	606.2	13.154	1.61	577.45	17.319	1.77	90.7	≤ 0.03	24.4
4	1144.8	8.735	1.38	1012.9	9.873	1.03	88.1	≤ 0.02	15.5
5	1565.0	6.390	1.4	1369.1	7.304	1.00	86.5	≤ 0.02	12.5
6	1941.1	5.152	0.92	1864.4	5.364	1.47	70.9	≤ 0.01	10.0
7	2387.9	4.188	0.28	2303.4	4.341	0.51	70.6	≤ 0.01	10.0
8	5153.4	1.940	1.04	4511.0	2.217	0.88	85.9	≤ 0.01	10.0
9	6420.5	1.558	0.99	5750.2	1.739	0.98	83.7	≤ 0.01	10.0
10	7965.2	1.255	1.06	7710.6	1.297	0.69	60.7	≤ 0.01	5.0

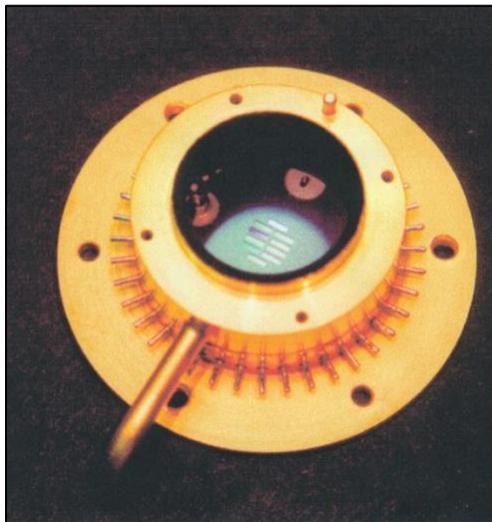
739
 740 Figure 19 shows the detector ceramic circuit board populated with detectors, JFETs,
 741 feedback resistors, and feedback capacitors. The height of each detector was adjusted to correct
 742 for the chromatic aberration caused by the filters. Electrical connections to the detector assembly
 743 were made by soldering shielded stainless steel wires to the radially protruding pins. Shielded
 744 stainless steel wires were used to minimize thermal conduction from the warm electronics to the
 745 detector assembly.



746

747 **Figure 19.** Populated detector ceramic circuit board installed in the bottom part of the detector
748 assembly.

749 Figure 20 shows the filter assembly installed in the bottom part of the detector assembly as
750 well as showing the top part of the detector assembly welded to the bottom part of the detector
751 assembly. This figure also shows the FPA purge tube protruding from the side wall of the top part
752 of the detector assembly, and the pin on the top of the detector assembly that was used to clock the
753 Lyot stop. This ensured the Lyot stop struts were aligned with the image of the secondary mirror
754 support struts.

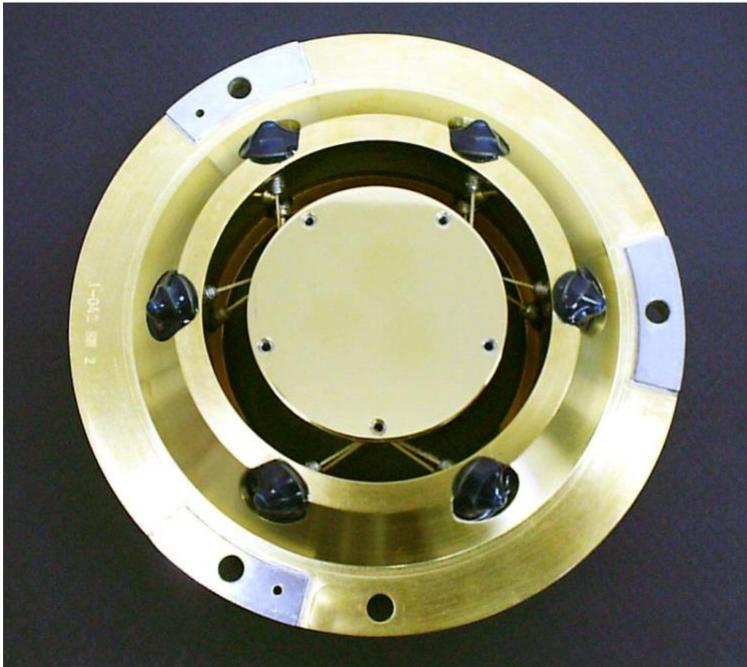


755

756 **Figure 20.** Filter array installed in bottom part of detector assembly and top part of detector
757 assembly welded to the bottom part of the detector assembly.

758 **4.8 SABER Fiber Support Technology (FiST)**

759 The SABER FPA assembly mount, which is shown in Figure 21, uses what SDL refers to
760 as Fiber Support Technology (FiST). This was a novel technique when SABER was built and
761 allowed the achievement of low thermal conduction from the telescope to the detector and the
762 cryocooler thermal link by using Kevlar fiber. This mount is very stiff with a first natural frequency
763 well above 500 Hz. The SABER FiST is bolted to the telescope at the three lapped pads on the
764 outer mounting ring (aluminum colored) in Figure 21. Pretensioned Kevlar strings support the
765 inner pedestal where the FPA is bolted. A very thin sheet, approximately 0.002” thick, was
766 sandwiched between the FPA and the FiST pedestal to maximize the thermal conductance between
767 them. A very flexible solderless thermal link with static stiffness measured to be less than 0.1
768 N/mm in all axes and a high thermal conductance (2.3 K/W) was bolted to the bottom surface of
769 the FiST pedestal and to the cryocooler cold block.



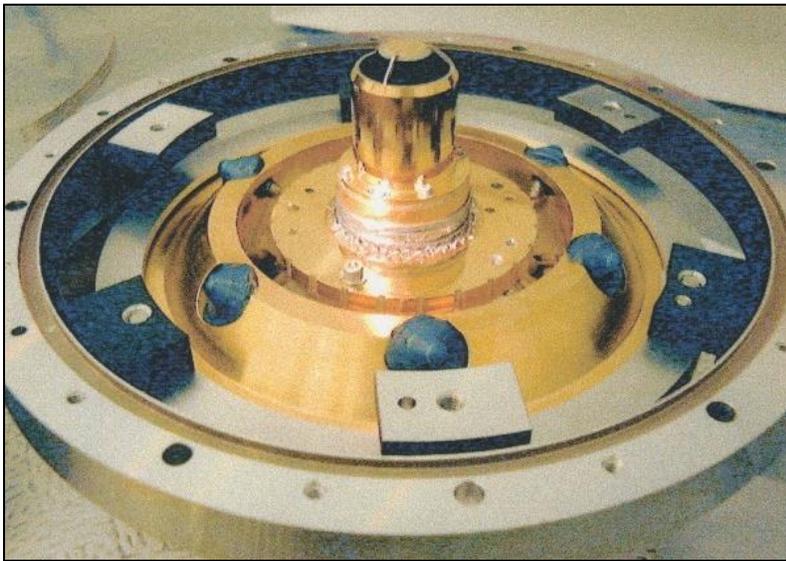
770

771 **Figure 21. SABER Fiber Support Technology**

772

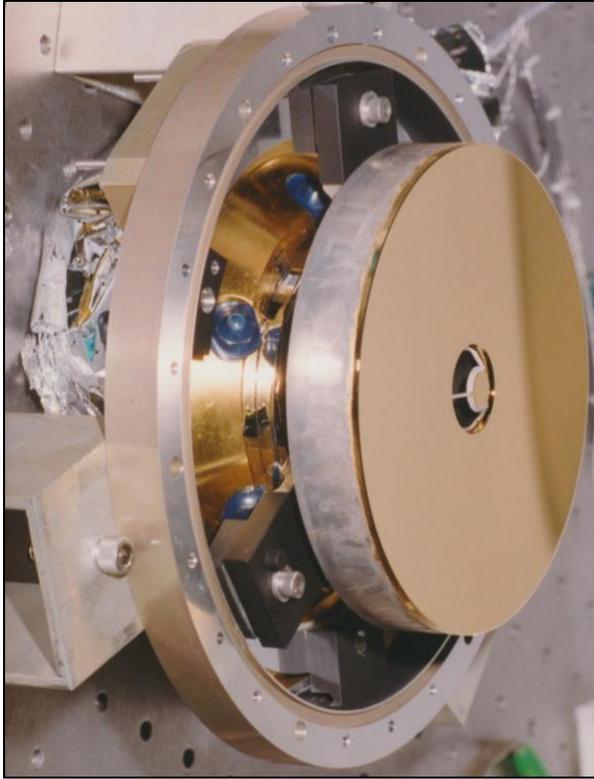
773 **4.9 SABER Lyot Stop**

774 The SABER Lyot Stop is shown mounted on the top of the FPA in Figure 22 and is shown
775 as item N in Figure 2. It is a novel 3-dimensional design that blocks light scattered and diffracted
776 from the edges of the aperture stop, the secondary mirror baffle, and the secondary mirror support
777 struts. Diffracted and scattered light from the edges of the aperture stop, which is few mm in front
778 of the primary mirror, is blocked by the outside edge of the circular Lyot stop opening that can be
779 seen in Figure 22. Diffracted and scattered light from the edges of the secondary mirror baffle is
780 blocked by the inner edge of the central obscuration of the Lyot stop. Diffracted and scattered light
781 from the three secondary mirror struts is blocked by the Lyot stop struts. The SABER Lyot stop
782 protrudes through the central hole of the tertiary mirror as can be seen in Figure 23.



783
784 **Figure 22.** Lyot stop mounted to the top of the FPA

785



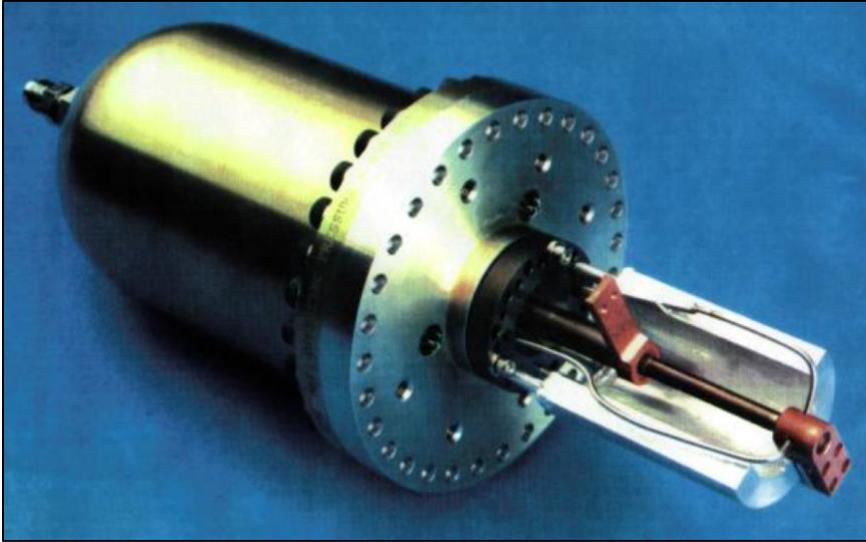
786

787 **Figure 23.** The SABER Lyot stop protrudes through a hole in the center of the tertiary mirror

788

789 **4.10 SABER Cryocooler**

790 Figure 24 shows the pulse-tube cryocooler used in SABER and developed by the TRW
791 Corporation in the mid-1990s. At the time SABER was built, this cryocooler was known as a
792 miniature cryocooler. This cooler has now been operating nearly continuously in space for over
793 21 years. The only time it has been turned off has been to enable evaporation of cryo-films that
794 are deposited over time on the FPA, flex link and cooler cold tip due to outgassing of MLI on the
795 outside of the SABER instrument, the other TIMED instruments, and the TIMED spacecraft.
796 Before launch, this cryocooler was run for several months in a US Air Force testing laboratory.
797 The approach to cooling SABER with this device is given in *Jensen et al.* (1998).



798

799 **Figure 24.** TRW miniature pulse tube cryocooler used for SABER.

800

801 ***4.11 SABER Electronics***

802 There are two types of analog signal processing channels in SABER, one type for PC
803 detectors and the other for PV detectors. The only configuration difference between these two
804 types is the preamplifiers. Preamplifiers for PC detectors use a voltage amplifier in the operating
805 temperature range of 245 K to 262 K to amplify the voltage across a biased PC detector operating
806 at 75 K. The preamplifiers for PV detectors use a TIA to amplify the current from the PV detectors.
807 The PV detector, a matched JFET pair, a feedback resistor, and a feedback capacitor are all
808 operating at 75 K while the operation amplifier that closes the feedback loop is operating in the
809 range of 245 K to 262 K. Thermal isolation between these two temperature zones is achieved by
810 using shielded stainless steel wires.

811 The remaining analog signal path architecture is the same for both PC and PV channels.
812 The preamplifier is followed by an instrumentation amplifier, which is followed by a 3-pole Bessel
813 bandpass filter centered on 1000 Hz, which is followed by a coherent rectifier stage that is phase
814 locked with the chopper, which is followed by a 4-pole low-pass Butterworth filter with a 4.545

815 Hz NEBW, which is followed by an voltage off-set adjustment stage, which is followed by a gain
 816 ranging stage with three gains, which is followed by a voltage follower stage to provide output
 817 isolation into a multiplexer, which is followed by a single instrument amplifier, which feeds a
 818 single sample-and-hold amplifier, which feeds a single 12-bit ADC, which feeds a 1553 interface
 819 stage, which finally feeds the TIMED Spacecraft electrical interface. The electronic power
 820 breakdown at the board level and by operation mode is given in Table 18.

821

822 **Table 18.** Electronic power breakdown at the board level and by operational mode.

Board Names	System	Calibration, Data Collection, Diagnostic Modes		Standby, Stabilization Modes		Power-up, Safe Modes	
		Avg.	Peak	Avg.	Peak	Avg.	Peak
		(watt)	(watt)	(watt)	(watt)	(watt)	(watt)
PC Channels 1-5	Signal Processing	2.3	2.3	2.3	2.3	0.0	0.0
PV Channels (6-10)	Signal Processing	2.2	2.2	2.2	2.2	0.0	0.0
Mux-A/D Converter	Signal Processing	1.0	1.0	1.0	1.0	0.0	0.0
DC/DC Converters (3)	Power	3.4	3.4	3.4	3.4	0.0	0.0
DC/DC Converters (4)	Power	8.3	10.4	8.3	8.3	0.0	0.0
DC/DC Converters (1 and 2)	Power	6.6	15.3	6.6	6.6	2.5	2.5
BB/JS/Heaters/Chop Cont & Sync	Analog Controllers/Chopper	0.9	3.3	0.9	0.9	0.0	0.0
Sys. Cntrl/Formatter/1553	Sys. Control & Data Handling	1.3	1.3	1.3	1.3	1.3	1.3
Scan Mirror Control/Driver	Scan Mirror Controller	1.2	1.5	1.2	1.2	0.0	0.0
Housekeeping (2)	Sys. Control & Data Handling	1.2	1.2	1.2	1.2	1.2	1.2
Housekeeping (1)	Sys. Control & Data Handling	0.6	0.6	0.6	0.6	0.6	0.6
Totals		29.0	42.5	29.0	29.0	5.6	5.6

823

824 **Summary**

825 The SABER instrument has been in orbit since 7 December 2001 and making routine
 826 science operations since 22 January 2002. As of this writing the instrument continues nominal
 827 operations. All standard data products are being produced on a regular schedule and made available
 828 to the public. More than 2,200 peer-reviewed journal articles have been published by scientists
 829 worldwide. The instrument has proven to be remarkably stable in its calibration after more than 21

830 years in orbit despite having an original planned mission life of 2 years. This remarkable and
831 sustained scientific output from SABER is attributable to the excellent quality of the radiances
832 measured by the SABER instrument and the excellent characterization of the instrument during its
833 development and testing. In this paper we have described the major systems and subsystems that
834 comprise the SABER instrument. It is evident that the skill and care taken to design, build,
835 calibrate, and operate SABER are major factors in its long lifetime and subsequent scientific
836 productivity.

837

838 **Open Research**

839 This paper provides a detailed technical description of the SABER instrument. There are
840 no scientific results reported herein and consequently no datasets to report. More detailed
841 information related to the procedures and tests used to calibrate the SABER instrument are
842 included in the SABER Ground Calibration report provided to NASA Langley by SDL. This report
843 and a separate file listing reference citations to the 2200 peer-reviewed journal articles using
844 SABER data are included as Supporting Information.

845

846 **Acknowledgements**

847 We would like to recognize the many organizations and people who have made the SABER
848 instrument such a success: The NASA Heliophysics Division; The Johns Hopkins University
849 Applied Physics Laboratory (JHU-APL); The NASA Goddard Space Flight Center; The NASA
850 Langley Research Center; Hampton University; The Space Dynamics Laboratory (SDL) of Utah
851 State University; Global Atmospheric Technologies and Science, Inc. We specifically
852 acknowledge Dr. Mary Mellott (NASA Headquarters, retired) for shepherding the TIMED mission
853 from its inception into formulation. In addition, we would like to acknowledge the mission Project
854 Scientists at NASA Goddard (Diego Janches) and at JHU-APL (Sam Yee) as well as the long-
855 serving TIMED Project Manager David Grant at JHU-APL. We remember our late colleagues
856 from Langley Research Center (James Miller, John Dodgen, Donald Robinson, and Anthony
857 Jalink), from SDL (James Ulwick and Doran Baker), and from NASA Goddard (Richard
858 Goldberg), all of whom contributed to the conception and development of SABER and TIMED.
859 We also thank Elisabeth Williams of SDL for help in producing this manuscript. Lastly, we
860 acknowledge the countless engineers, technicians, scientists, financial analysts, contract
861 specialists, and others whose diligence and remarkable expertise on a daily basis throughout the
862 development of SABER and TIMED ultimately enabled the mission and thus incredible scientific
863 and technical careers for the authors and for hundreds of scientists worldwide.

864

865 **Reference Citations**

- 866 Brown, S. M. Jensen, S. Jensen, G. Hansen, L. Zollinger, R. Esplin, J. B. Miller, (2006). Sounding
867 of the atmosphere using broadband emission radiometry (SABER): sensor design,
868 performance, and lessons learned, Proceedings of SPIE 6297, doi: [10.1117/12.684137](https://doi.org/10.1117/12.684137)
- 869 Dyer, J., S. Brown, R. Esplin, G. Hansen, S. Jensen, J. Stauder, and L. Zollinger, (2002).
870 Contamination Control of the SABER Cryogenic Infrared Telescope. Proceedings of
871 SPIE 4774, <https://doi.org/10.1117/12.481652>
- 872 Hansen, S., J. Peterson, R. Esplin, and J. Tansock, (2003). Component level prediction versus
873 system level measurement of SABER relative spectral response, International Journal of
874 Remote Sensing, <https://doi.org/10.1080/01431160304968>
- 875 Jensen, S., J. C. Batty, W. A. Roettker, M. J. Felt, (1998). Cooling SABER with a miniature pulse
876 tube refrigerator, Proceeding of SPIE 3435, <https://doi.org/10.1117/12.323740>
- 877 Mlynczak, M. G., L. A. Hunt, R. R. Garcia, V. L. Harvey, B. T. Marshall, J. Yue, C. J. Mertens,
878 and J. M. Russell, (2022). Cooling and contraction of the Mesosphere and Lower
879 Thermosphere from 2022 to 2021, *J. Geophys. Res. – Atmospheres*,
880 <https://doi.org/10.1029/2022JD036767>
- 881 Mlynczak, M. G., J. Yue, J. McCormack, R. S. Liebermann, and N. J. Livesey (2021), An
882 observational gap at the edge of space, *Eos*, 102, <https://doi.org/10.1029/2021EO155494>.
- 883 Mlynczak, M. G., et al., (2020). Radiometric stability of the SABER instrument. Earth and Space
884 Science, <https://doi.org/10.1029/2019EA001011>
- 885 Mlynczak, M. G., (1997) Energetics of the mesosphere and lower thermosphere and the SABER
886 experiment, *Advances in Space Research*, Volume 20, Issue 6, 1997, Pages 1177-1183,
887 [https://doi.org/10.1016/S0273-1177\(97\)00769-2](https://doi.org/10.1016/S0273-1177(97)00769-2)

888 Mlynczak, M. G., (1996). Energetics of the middle atmosphere: Theory and observation
889 requirements, *Advances in Space Research*, Volume 17, Issue 11, Pages 117-126,
890 [https://doi.org/10.1016/0273-1177\(95\)00739-2](https://doi.org/10.1016/0273-1177(95)00739-2).

891 Mlynczak, M. G., S. Solomon, (1993). A detailed evaluation of the heating efficiency in the
892 middle atmosphere, *J. Geophys. Res.*, 98(D6), 10517-10541, 10.1029/93JD00315.

893 Russell III, James M., M. G. Mlynczak, L. L. Gordley, J. J. Tansock, Jr., and R. W. Esplin,
894 (1999). Overview of the SABER experiment and preliminary calibration results Proc.
895 SPIE 3756, 277 (1999), DOI:10.1117/12.366382.

896 Stauder, J., R. Esplin, L. Zollinger, M. Mlynczak, J. Russell III, L. L. Gordley, and B. T.
897 Marshall, Stray light analysis of the SABER telescope, Proceedings of SPIE 2553,
898 <https://doi.org/10.1117/12.221362>

899 Tansock, J., et al. (2003). SABER ground calibration. *International Journal of Remote Sensing*,
900 24(2), 403–420. <https://doi.org/10.1080/01431160304969>

901

Figure 1.

12/1/2003

7/1/2020

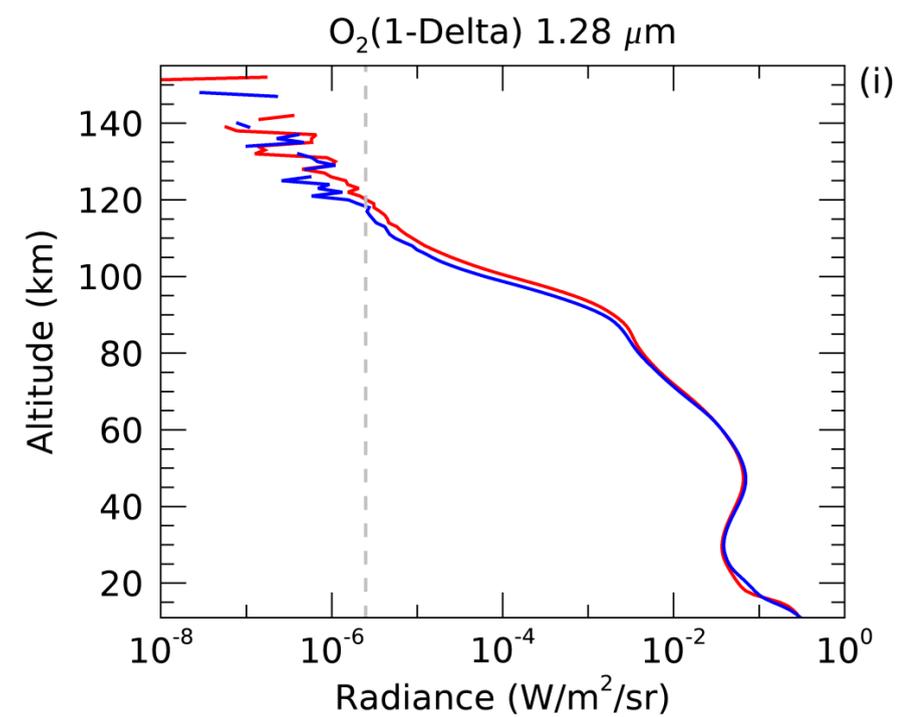
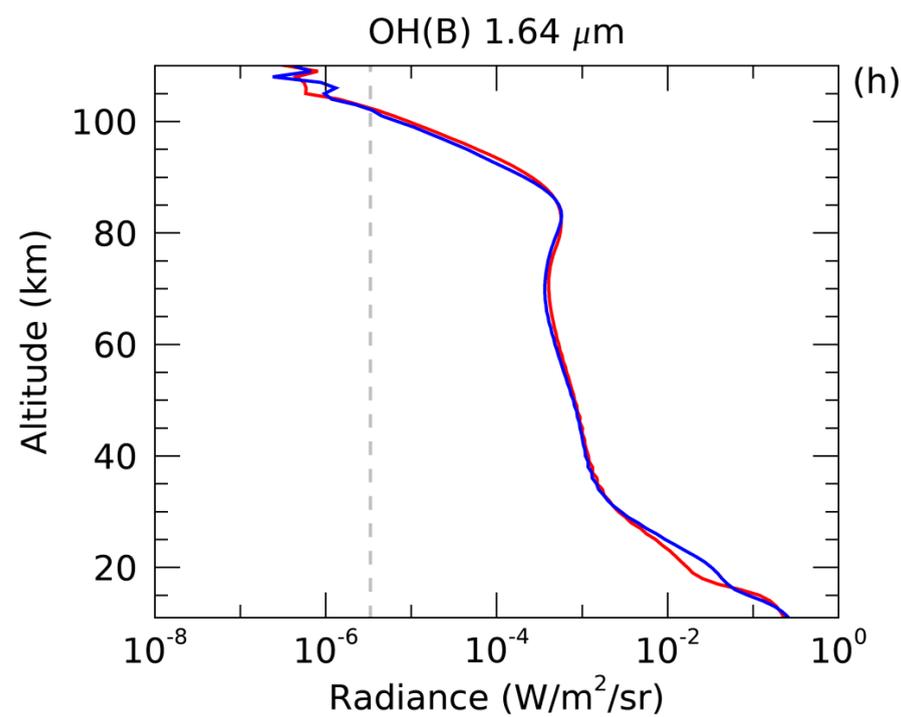
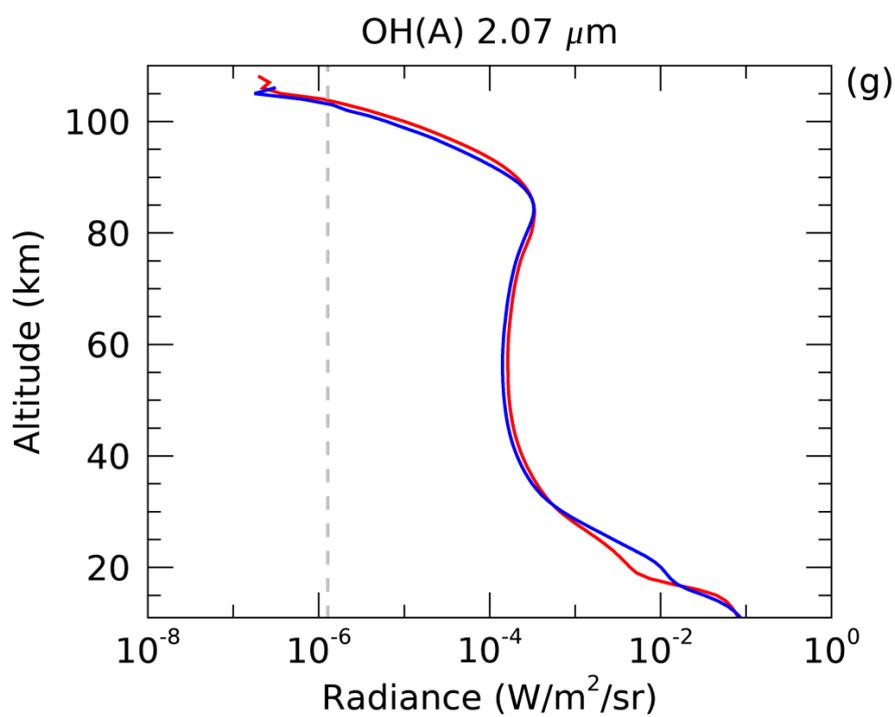
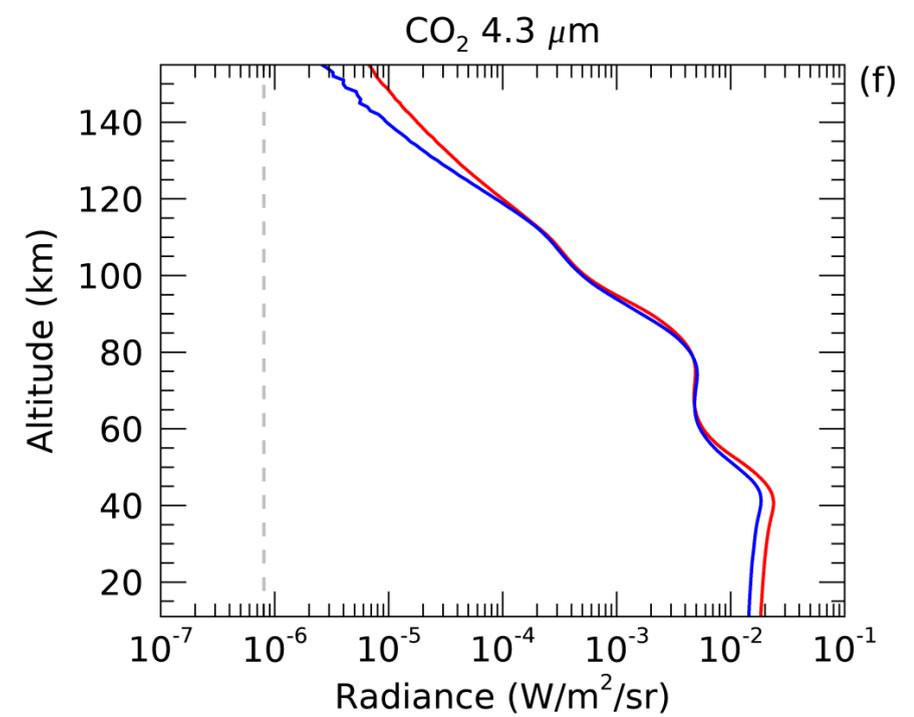
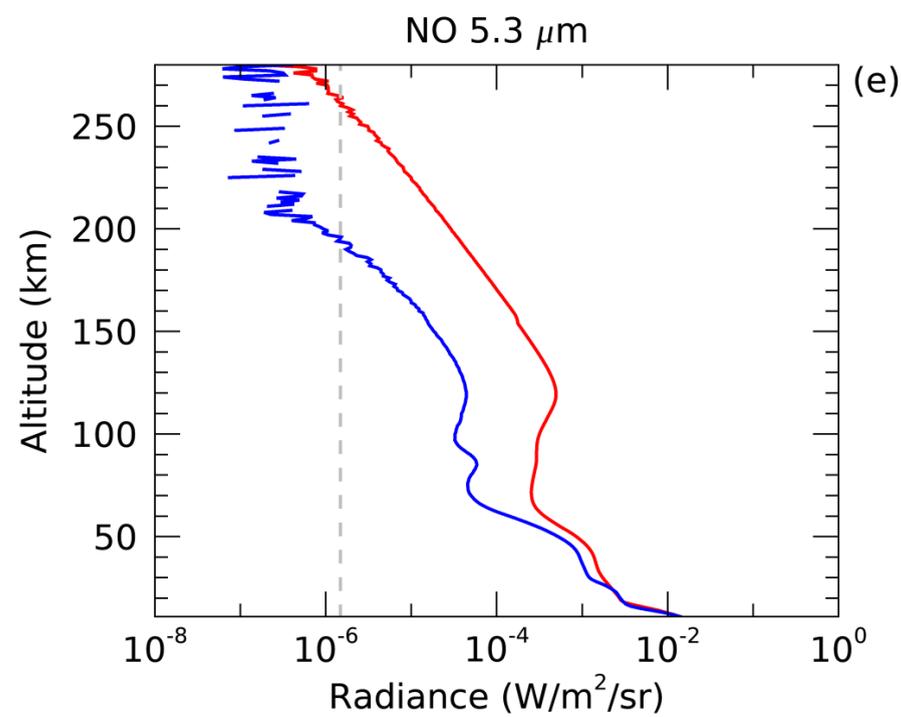
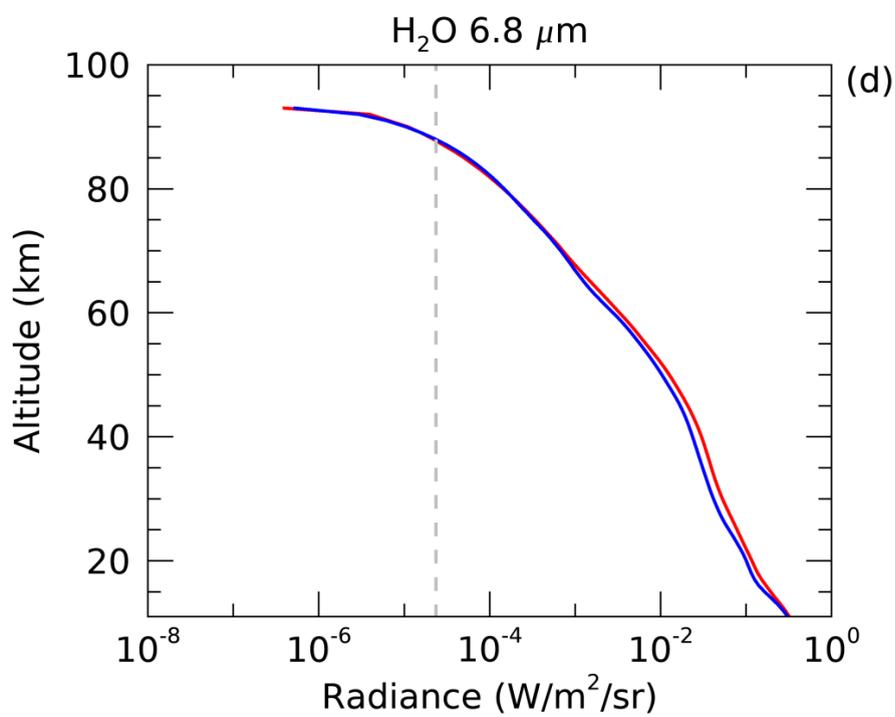
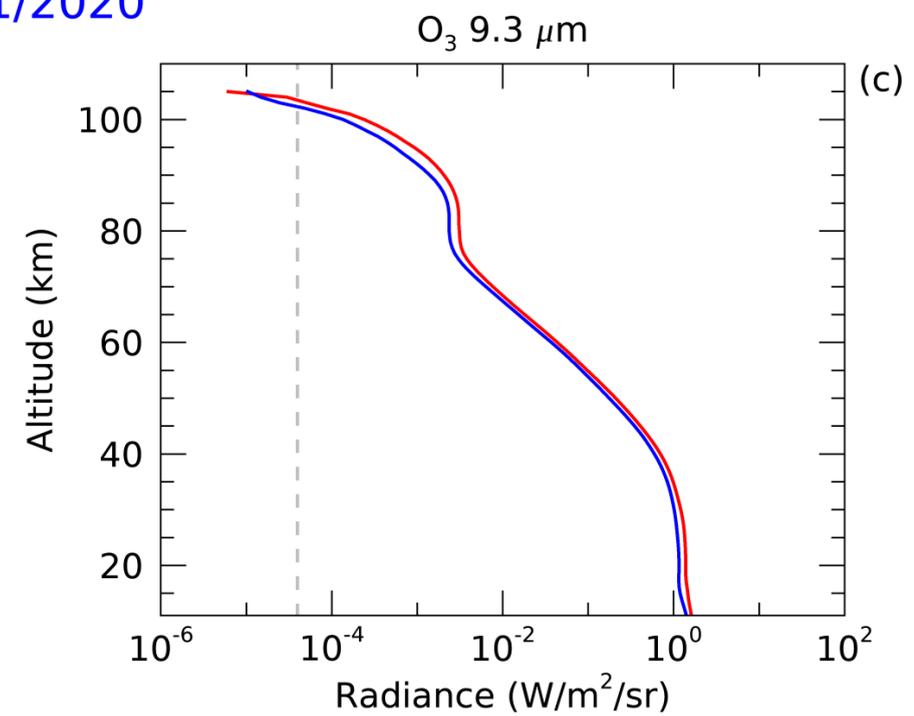
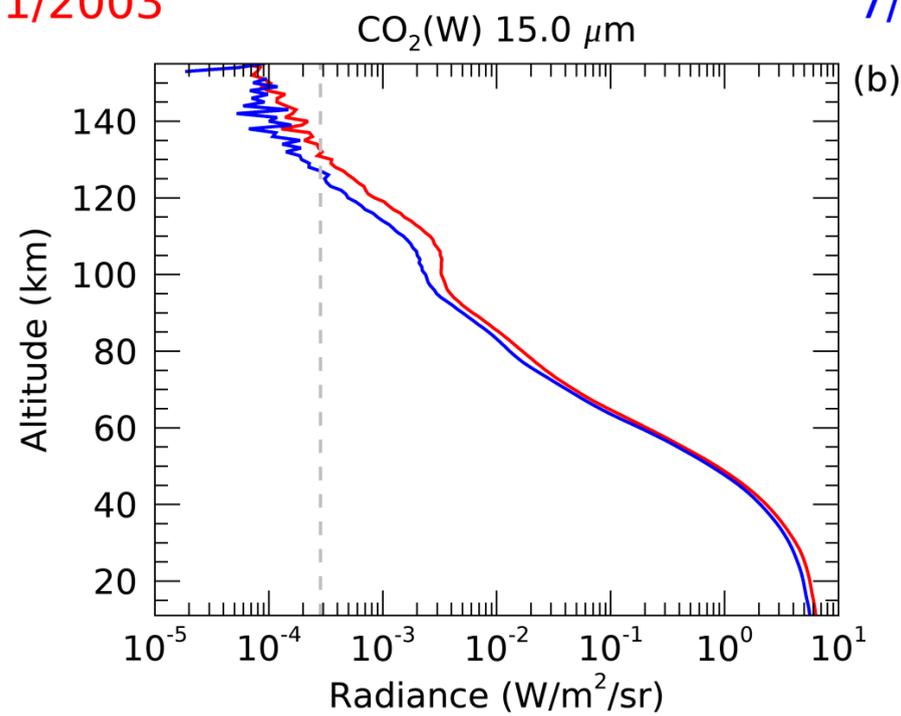
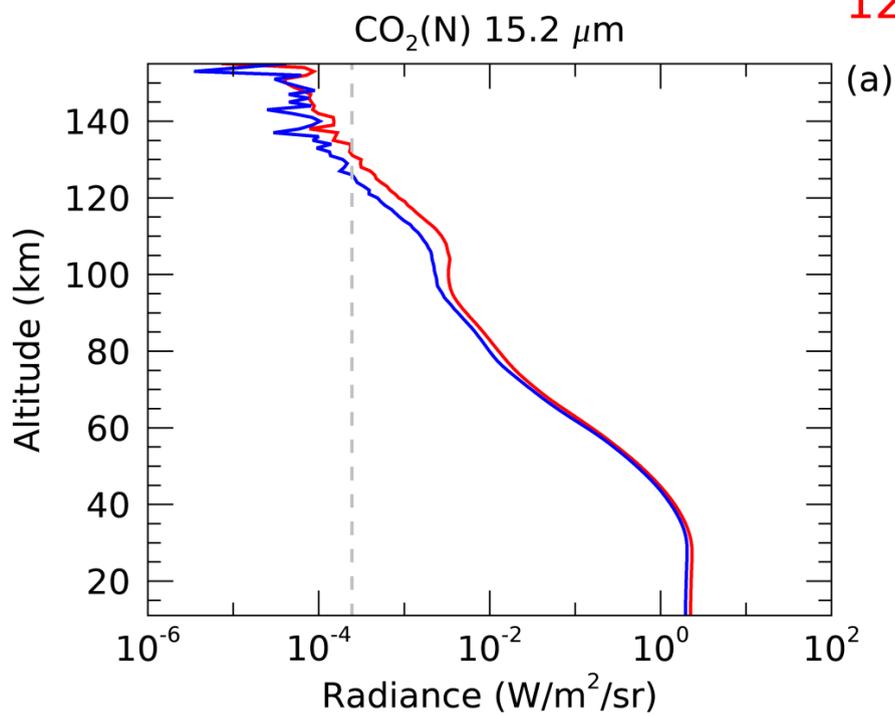


Figure 2.

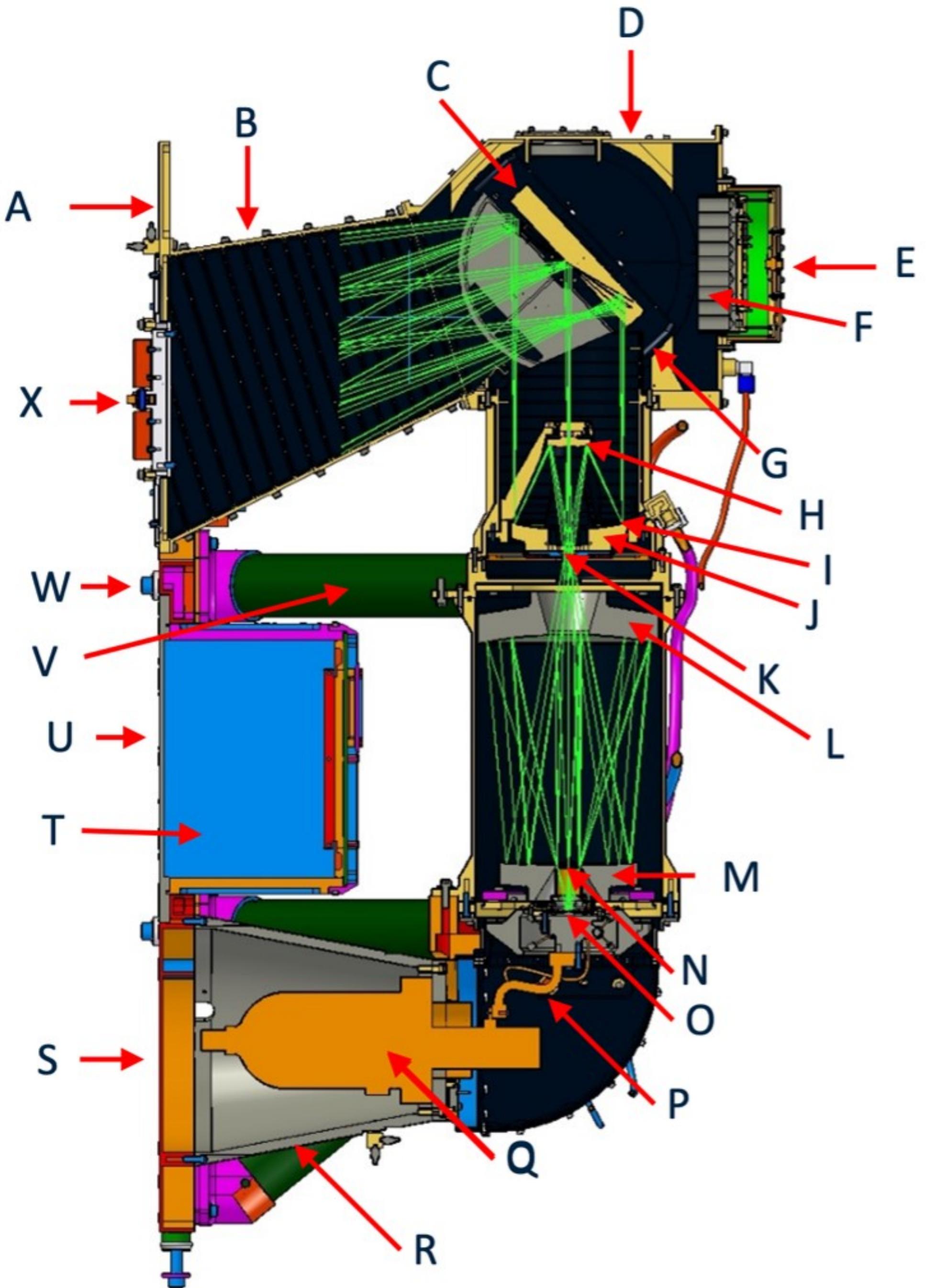


Figure 3.



Figure 4.

TME
D
TME

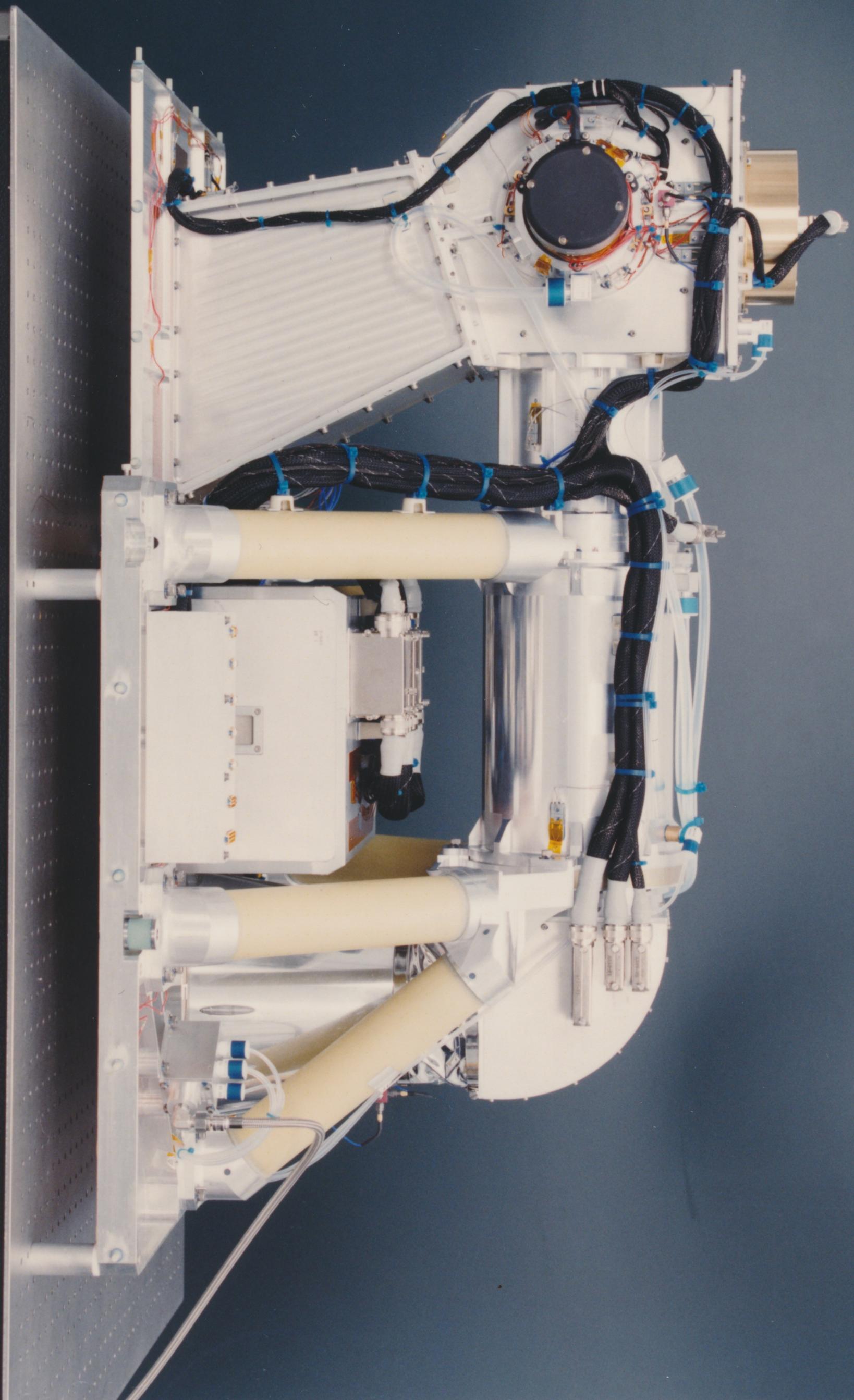


Figure 5.

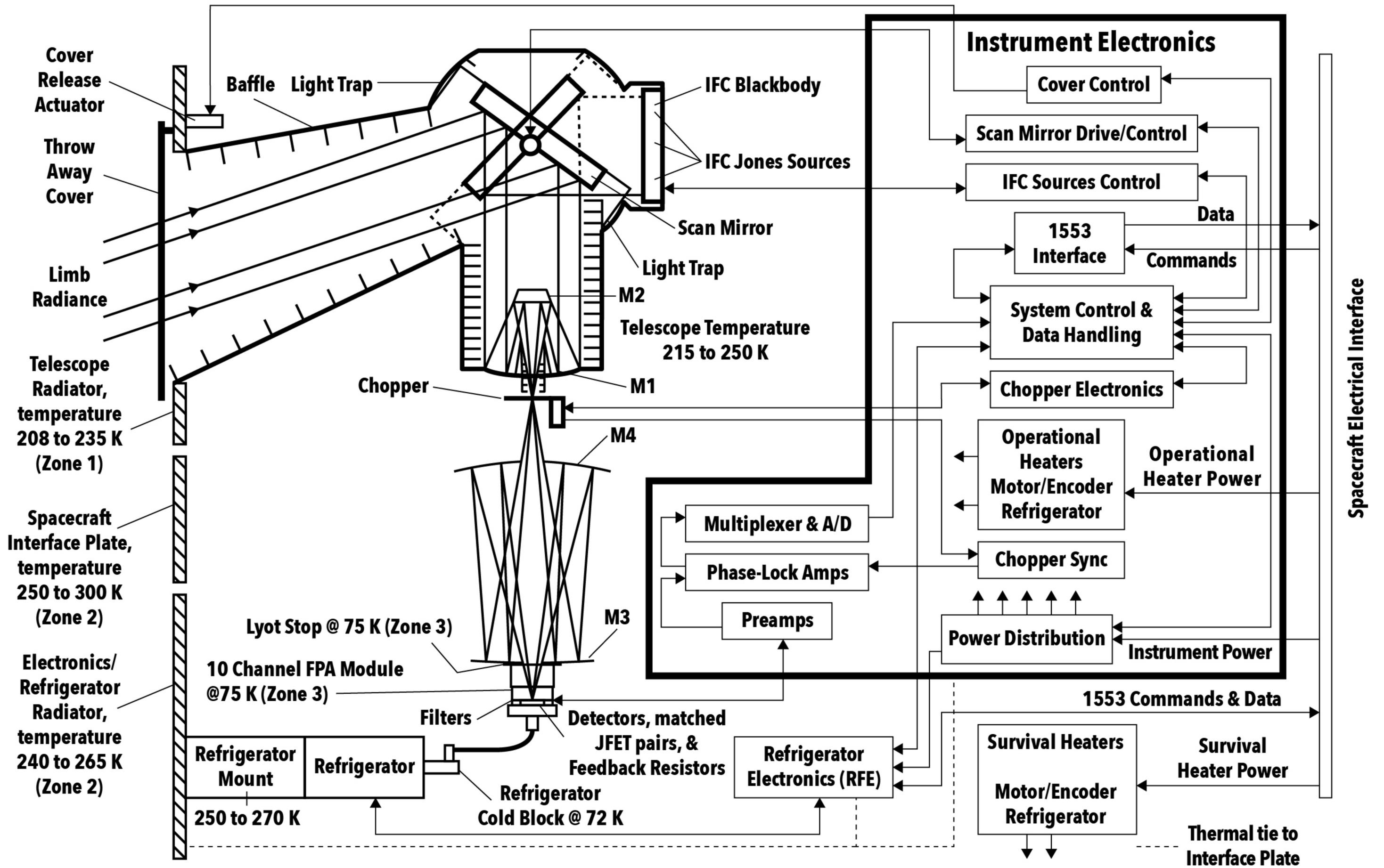
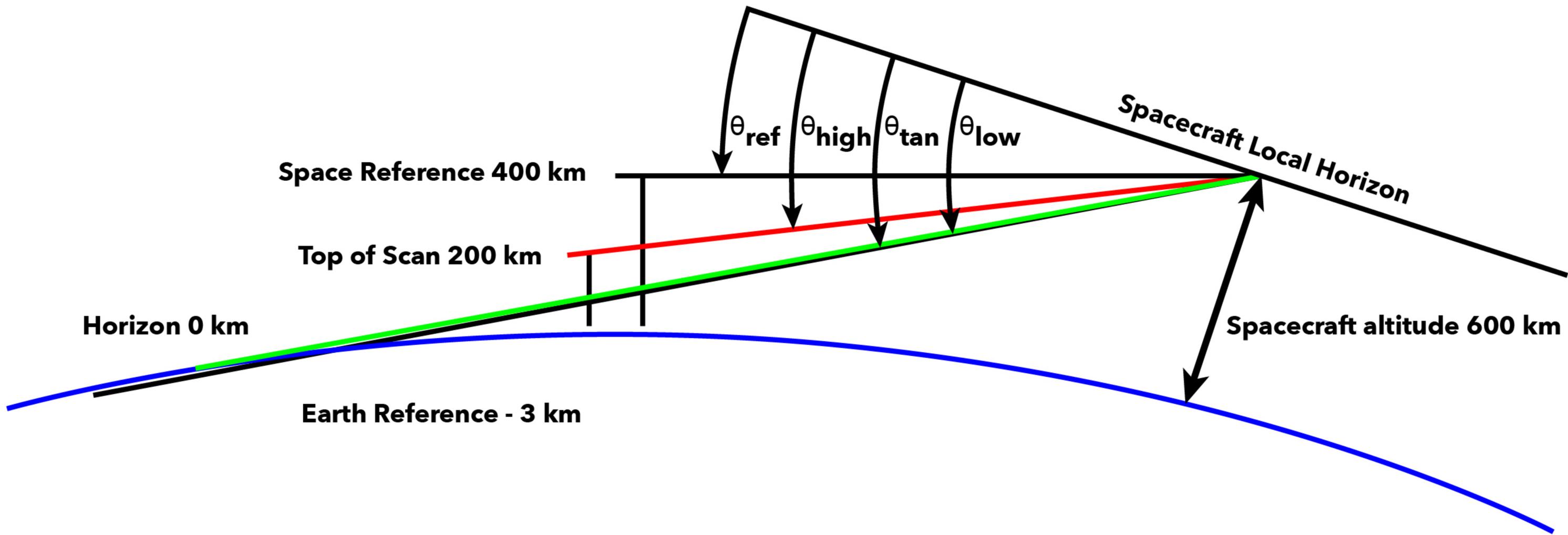


Figure 6.



Horizon 0 km

Space Reference 400 km

Top of Scan 200 km

Earth Reference - 3 km

Spacecraft altitude 600 km

Spacecraft Local Horizon

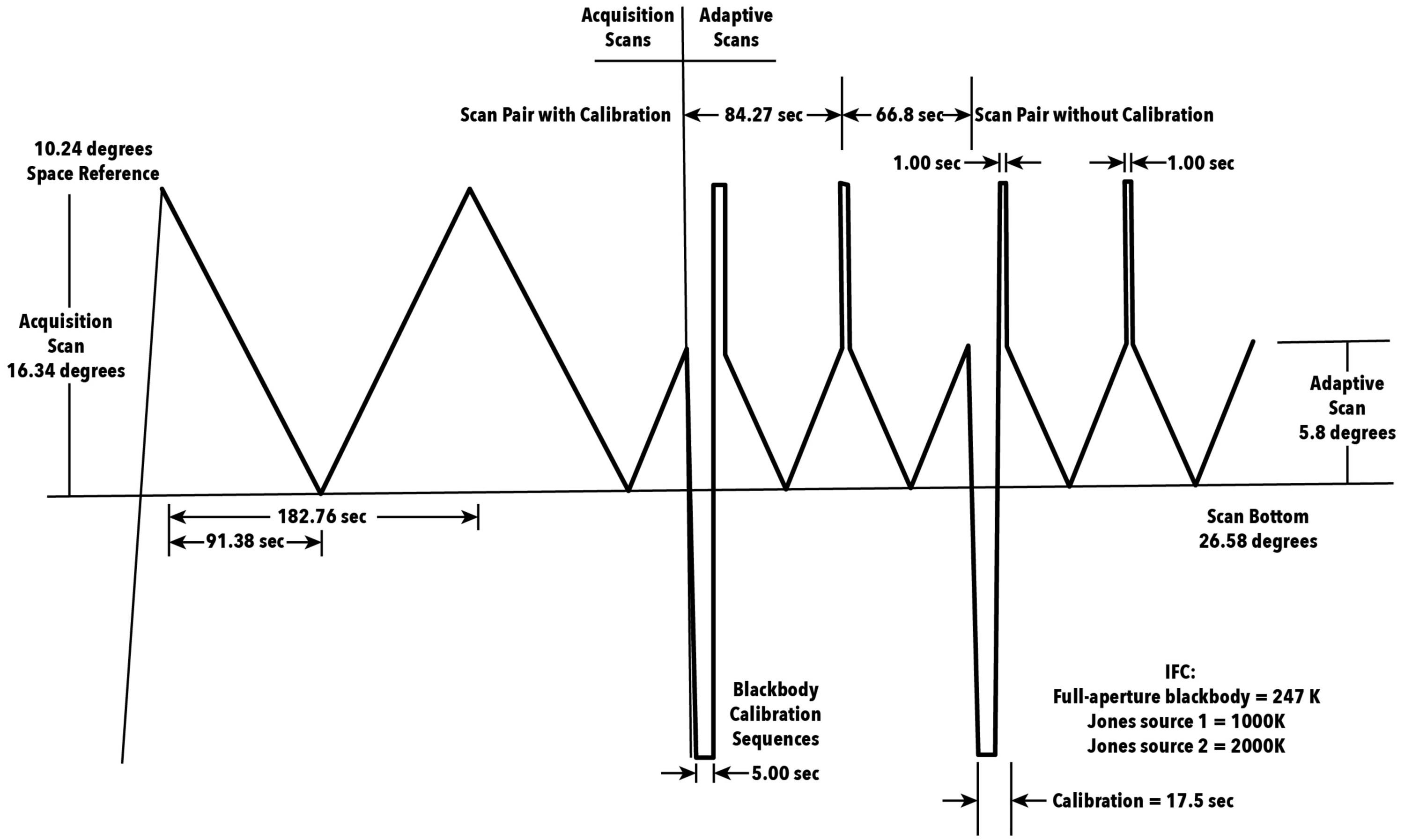
θ_{ref}

θ_{high}

θ_{tan}

θ_{low}

Figure 7.



Not to Scale

Figure 8.

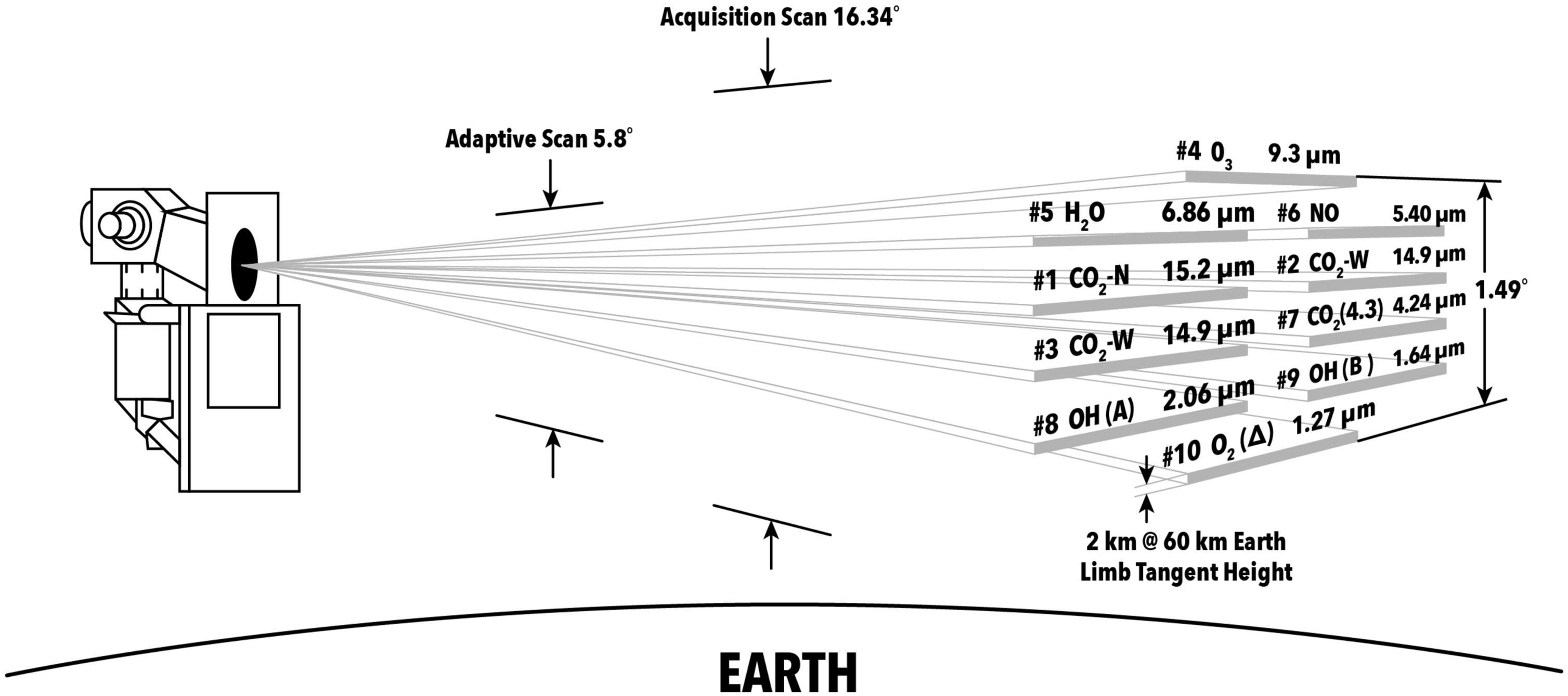


Figure 9.

Witness Mirrors

Scan
Motor and
Bearing
Housing

IFC
Blackbody

Chopper
Location

Purge Inlet
Connection and
Filtered Manifold

Launch
Depressurization
Relief Valve

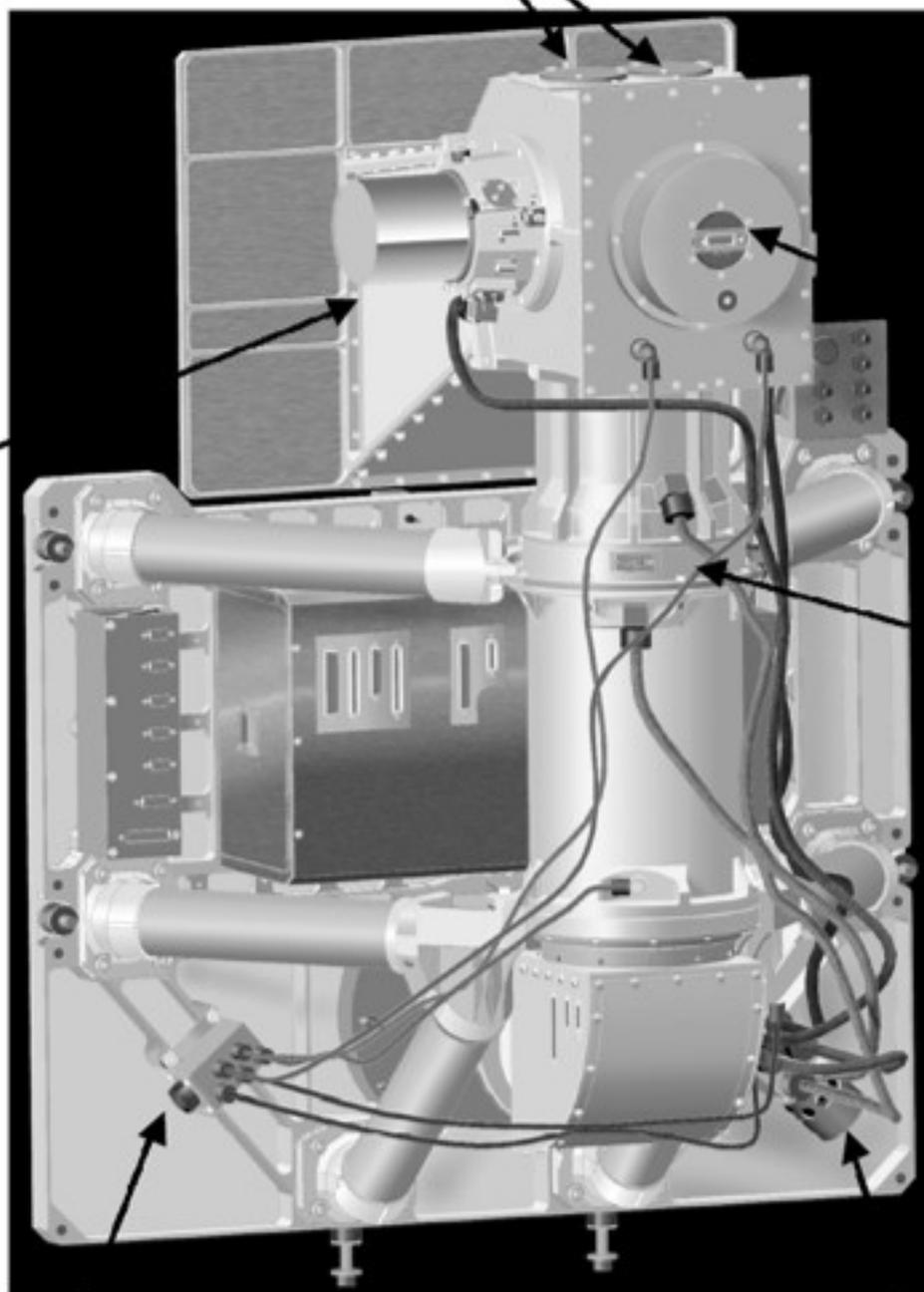


Figure 10.

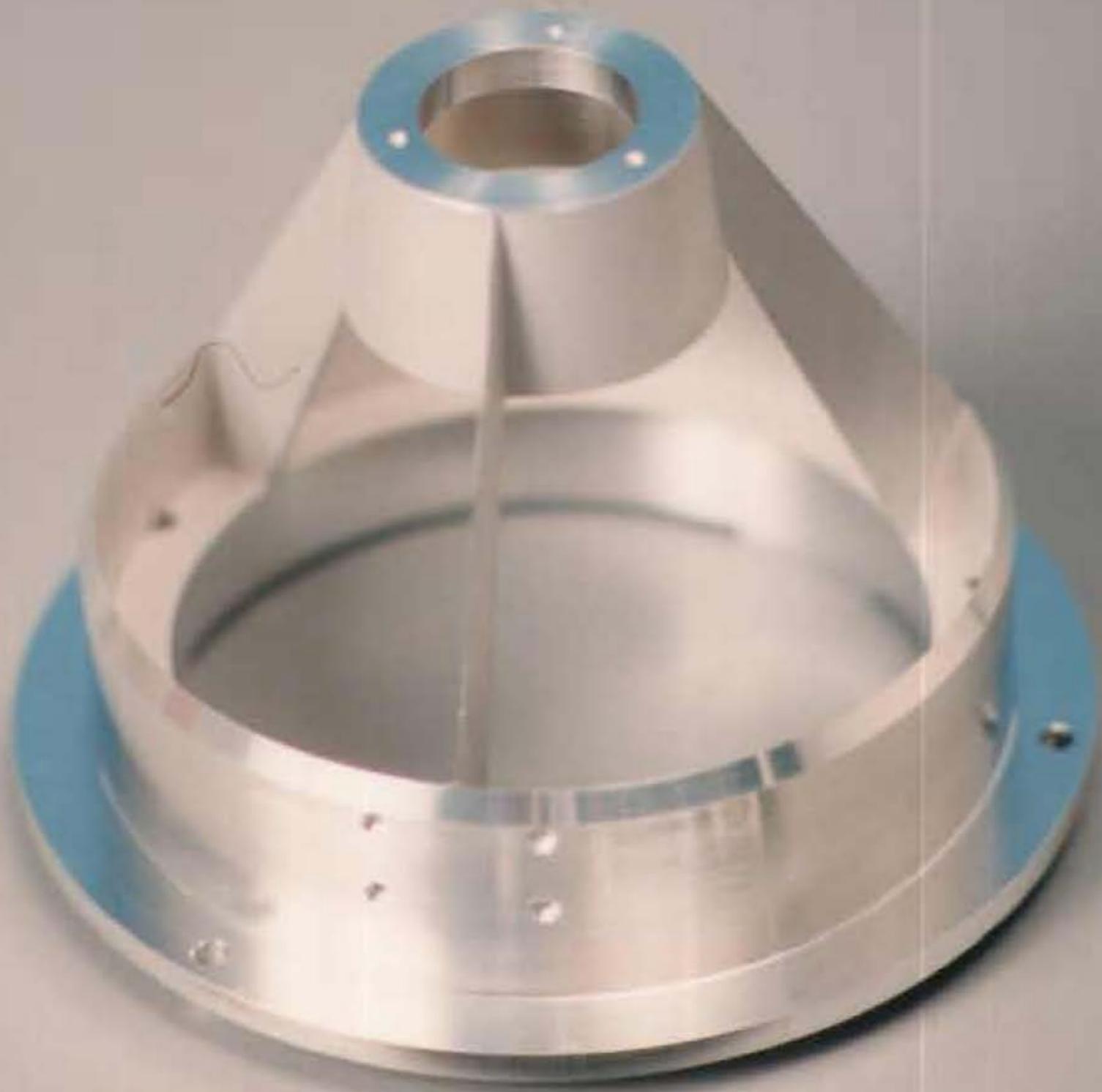


Figure 11.

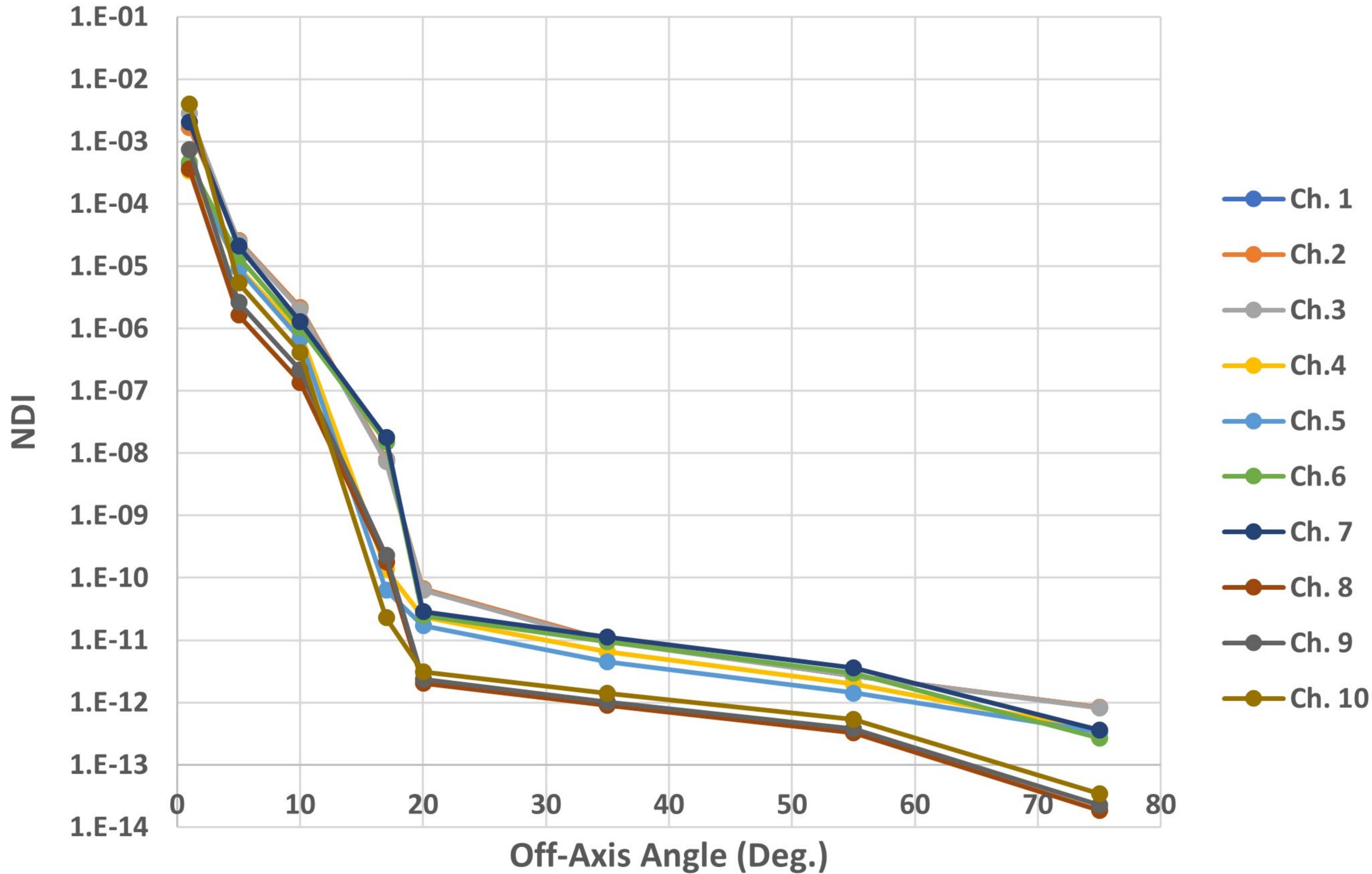


Figure 12.

(a)



(b)

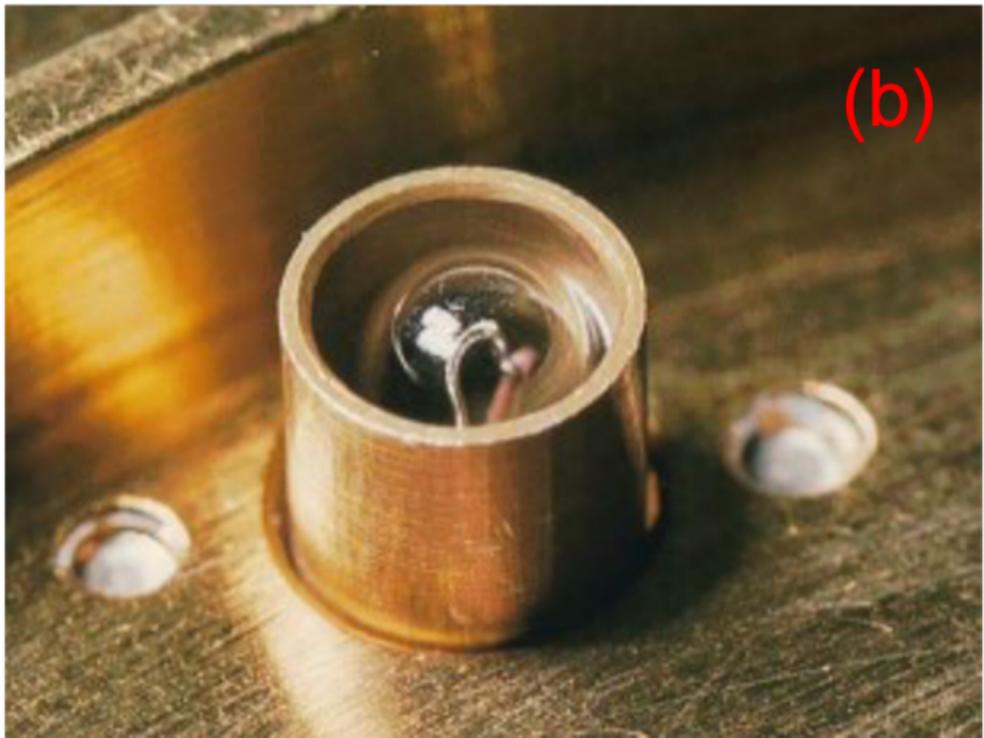


Figure 13.

Wax
Actuator
Pin
Puller



Cover
Witness
Mirrors

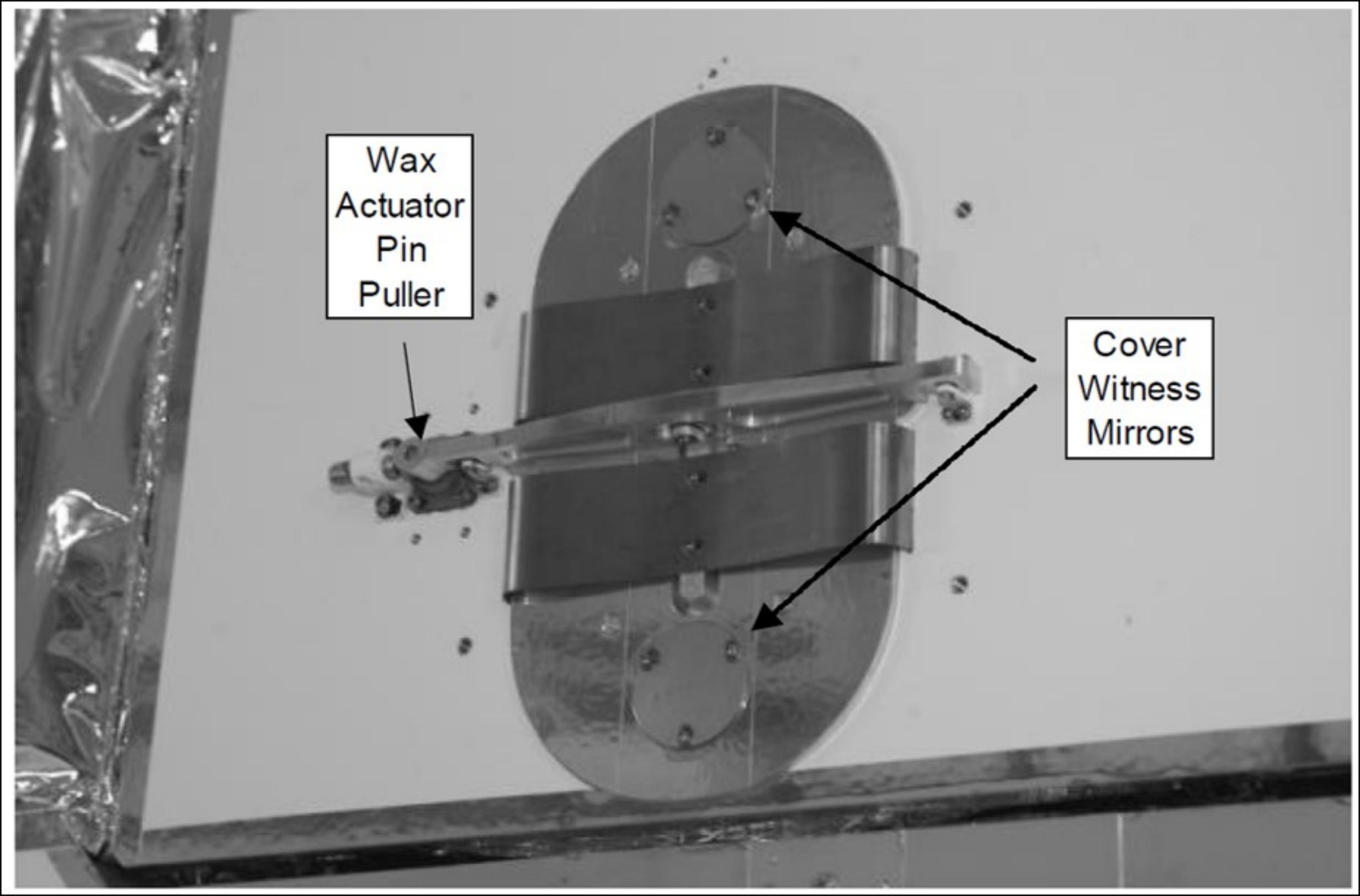
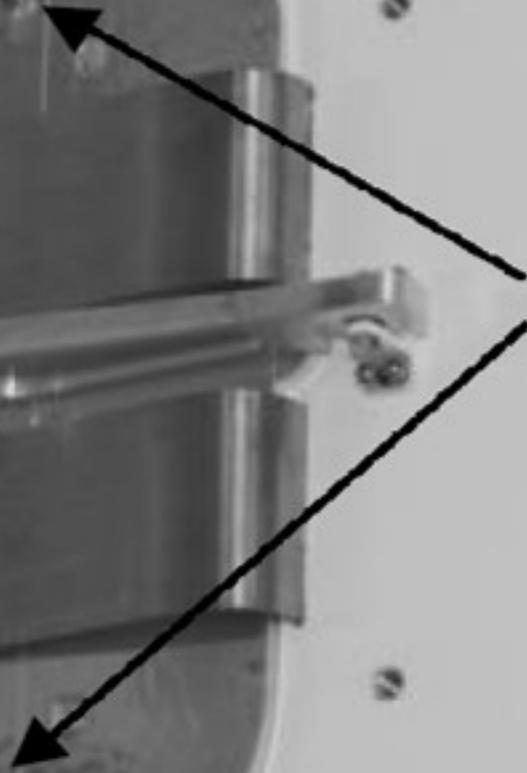


Figure 14.

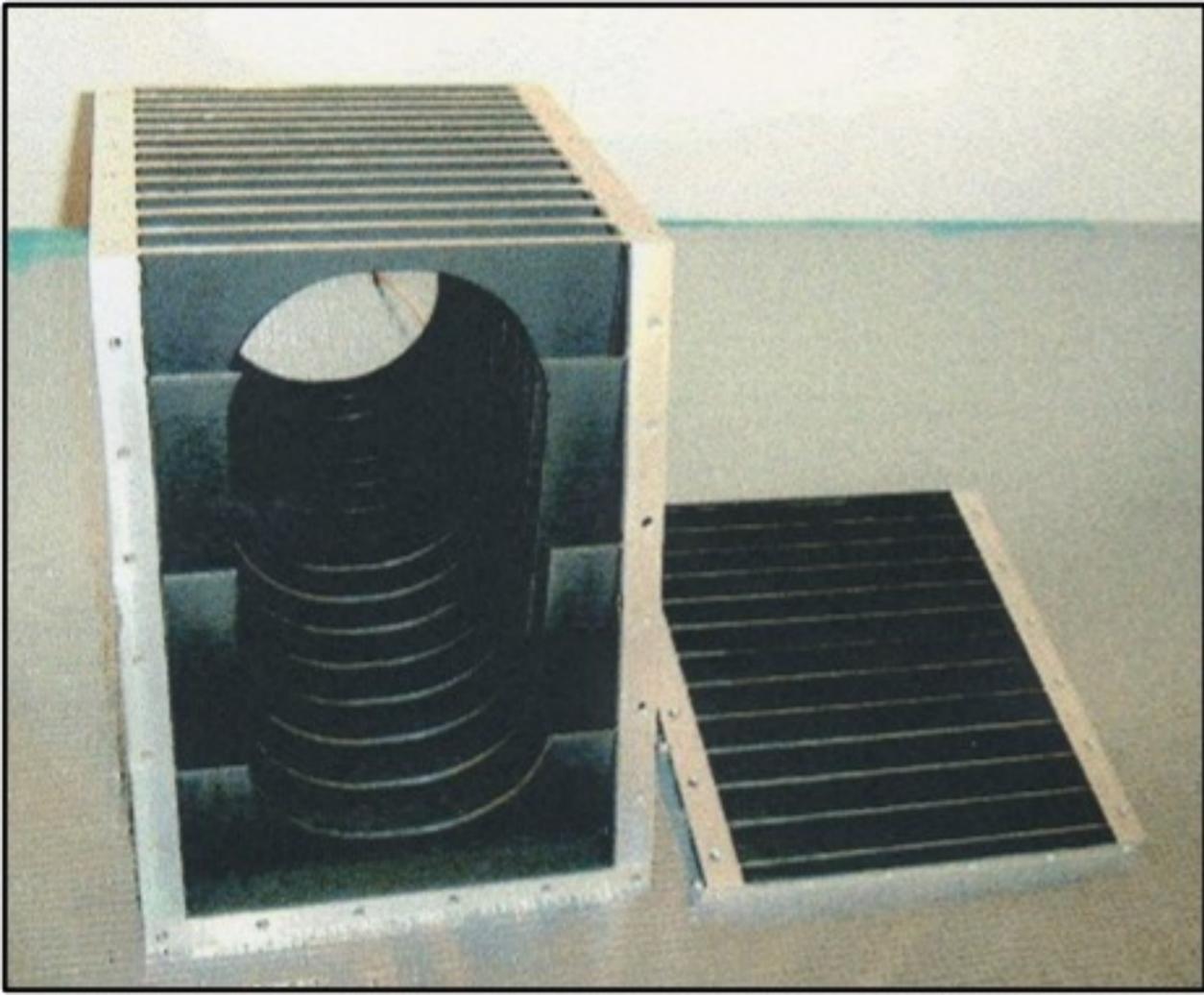


Figure 15.

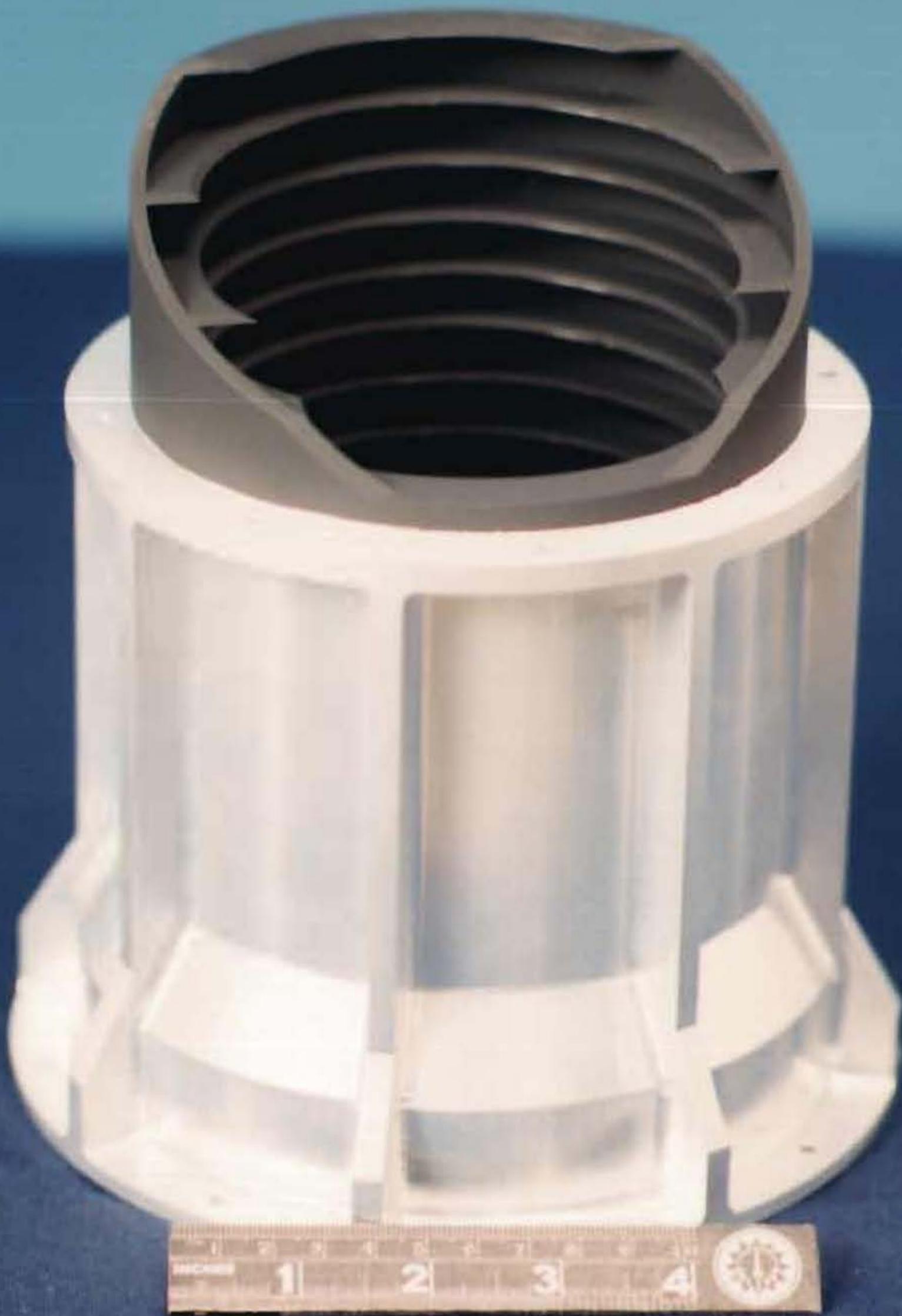
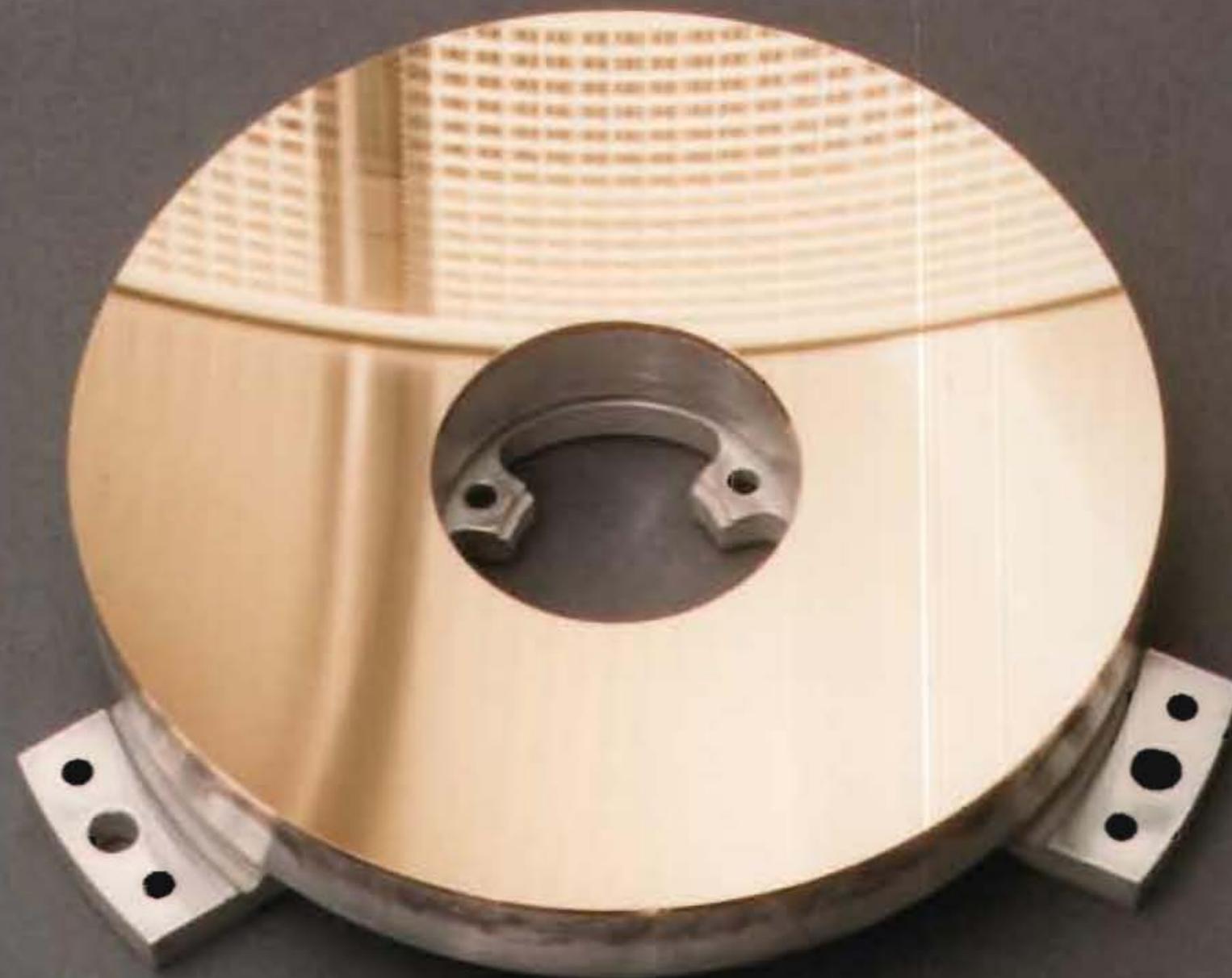


Figure 16.



 **SABER M1**

Figure 17.

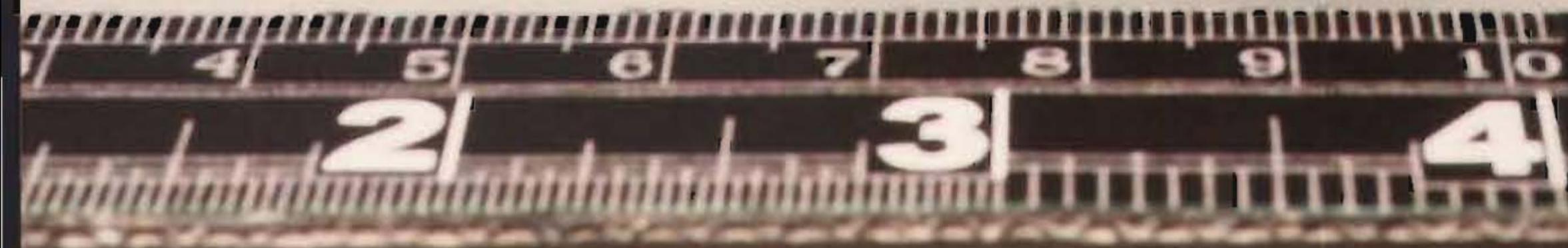


Figure 18.

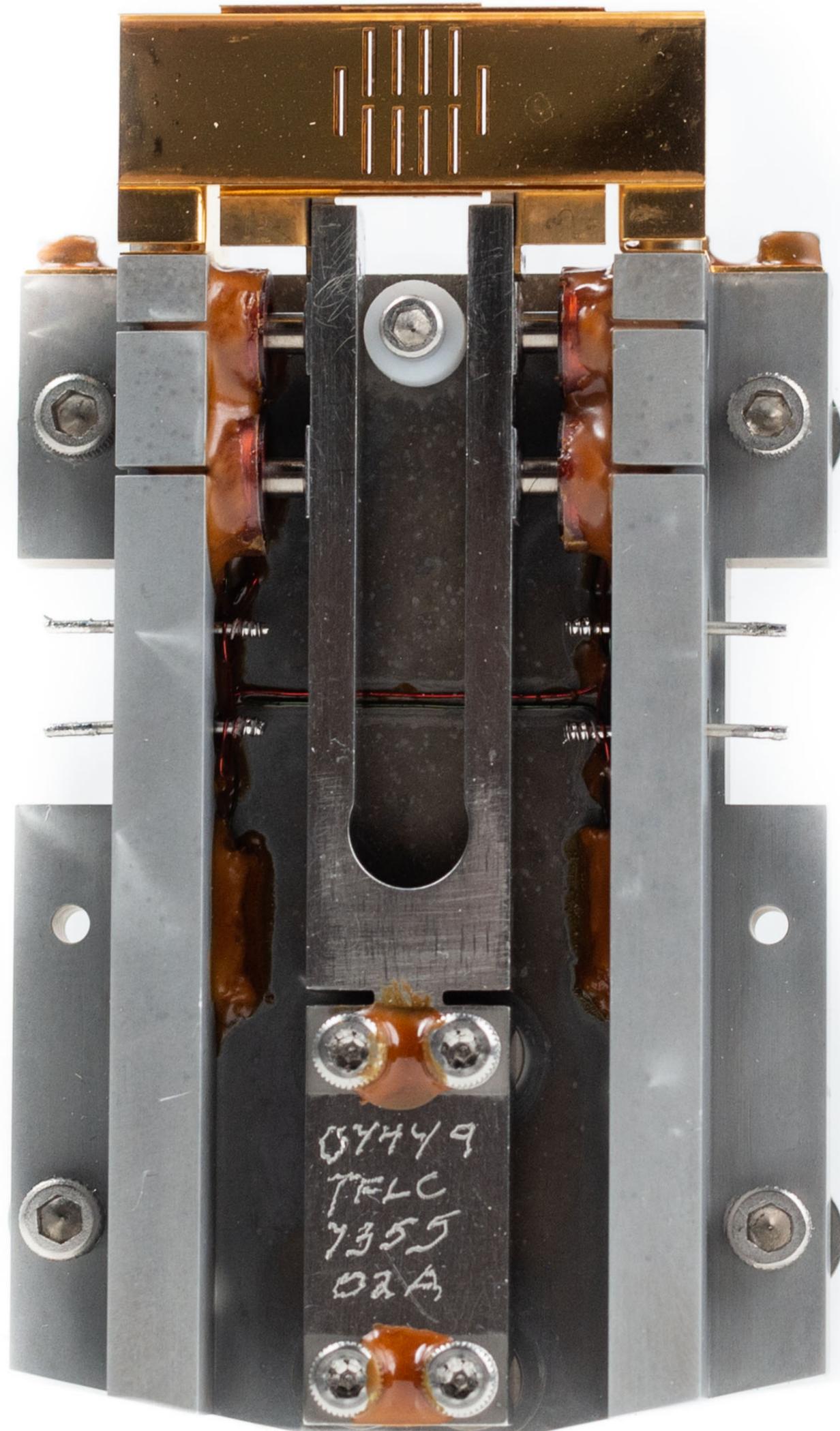


Figure 19.

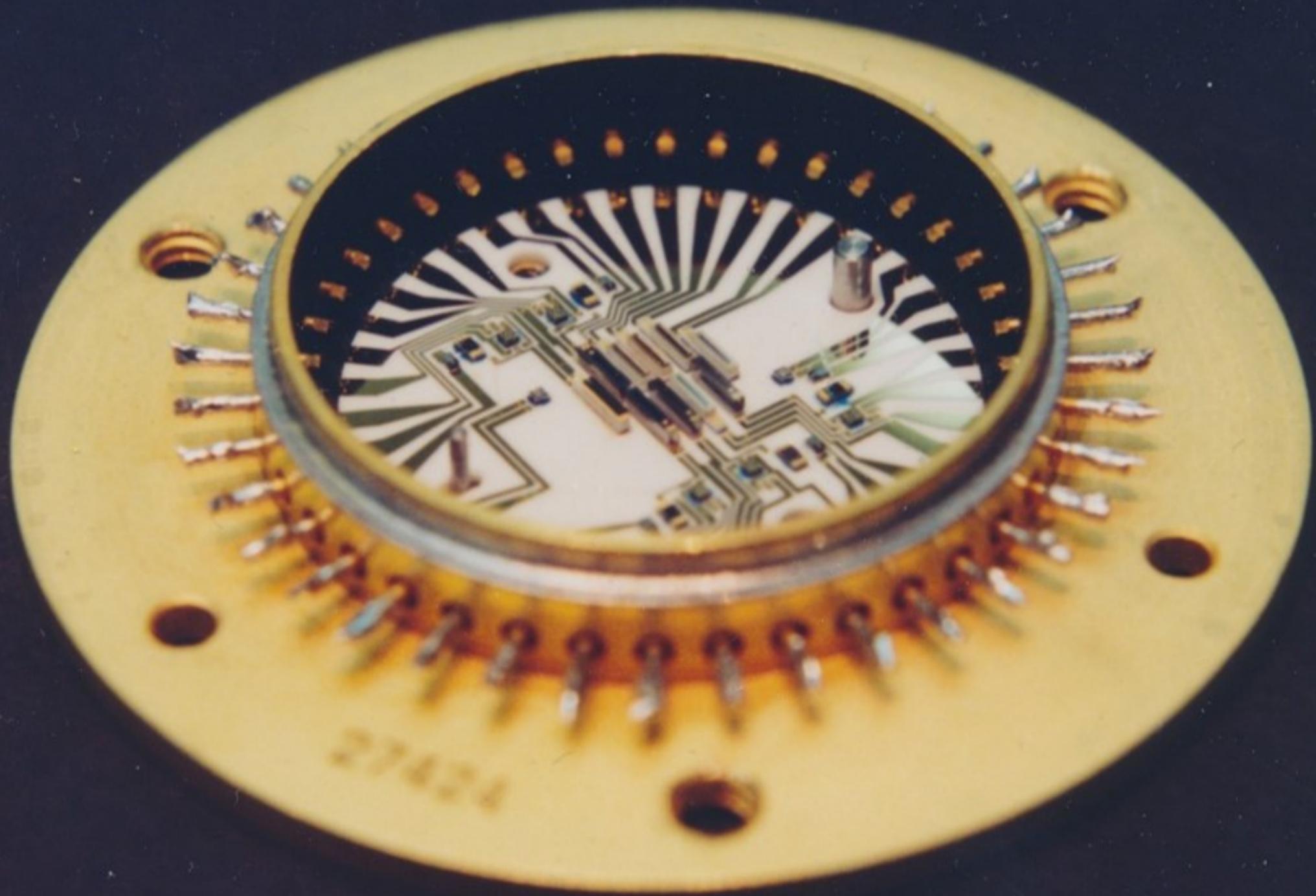


Figure 20.

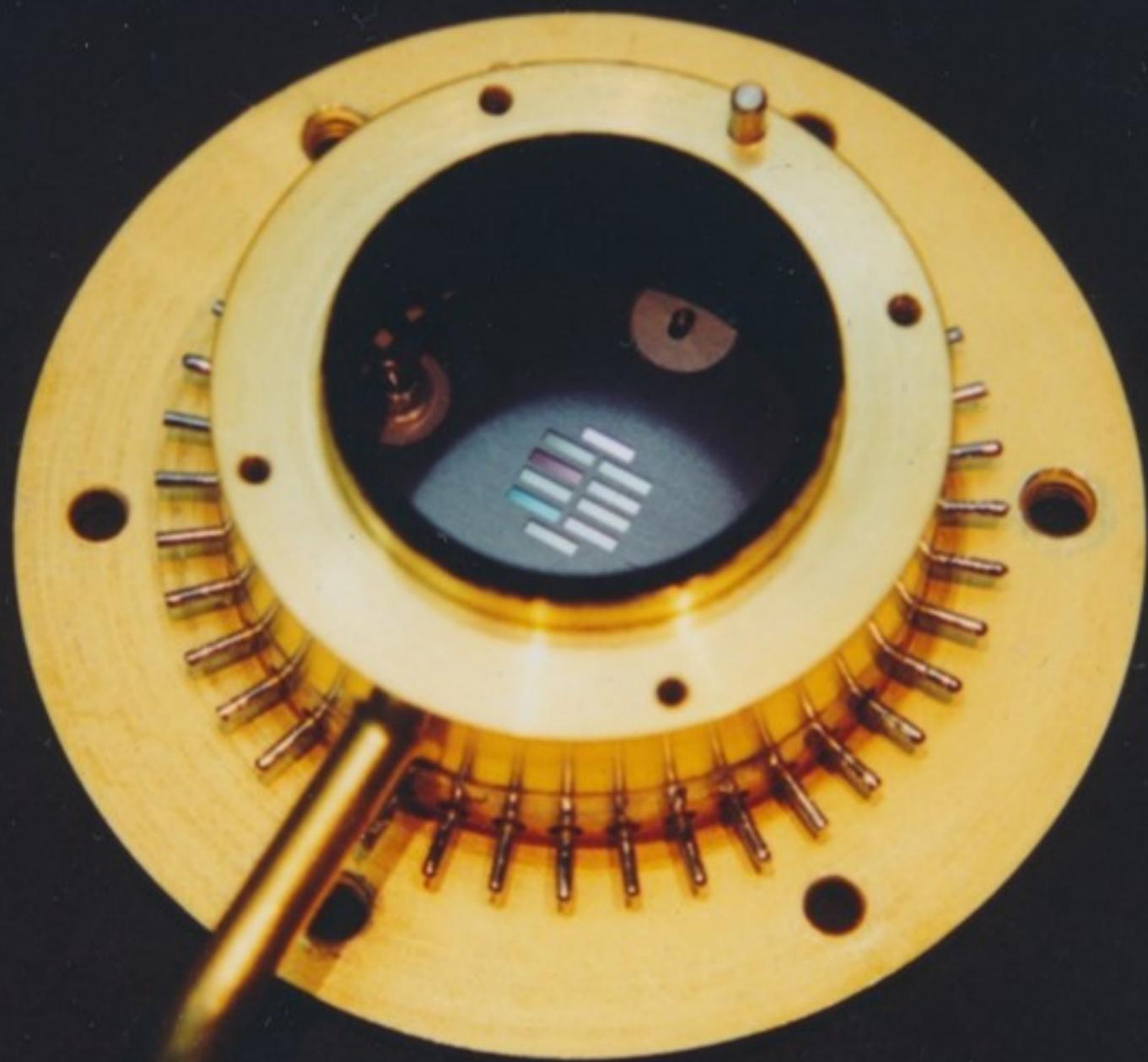


Figure 21.

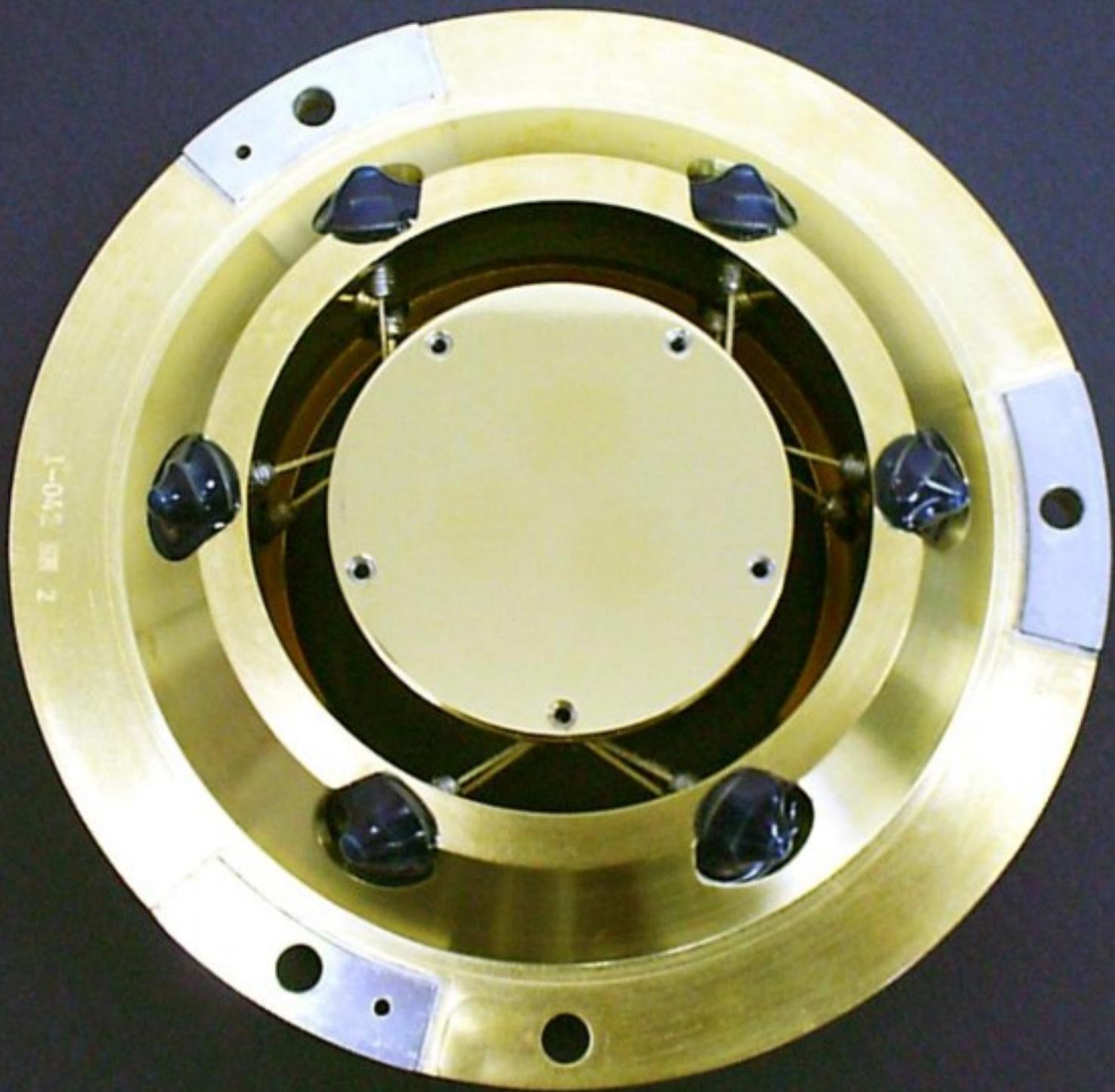


Figure 22.

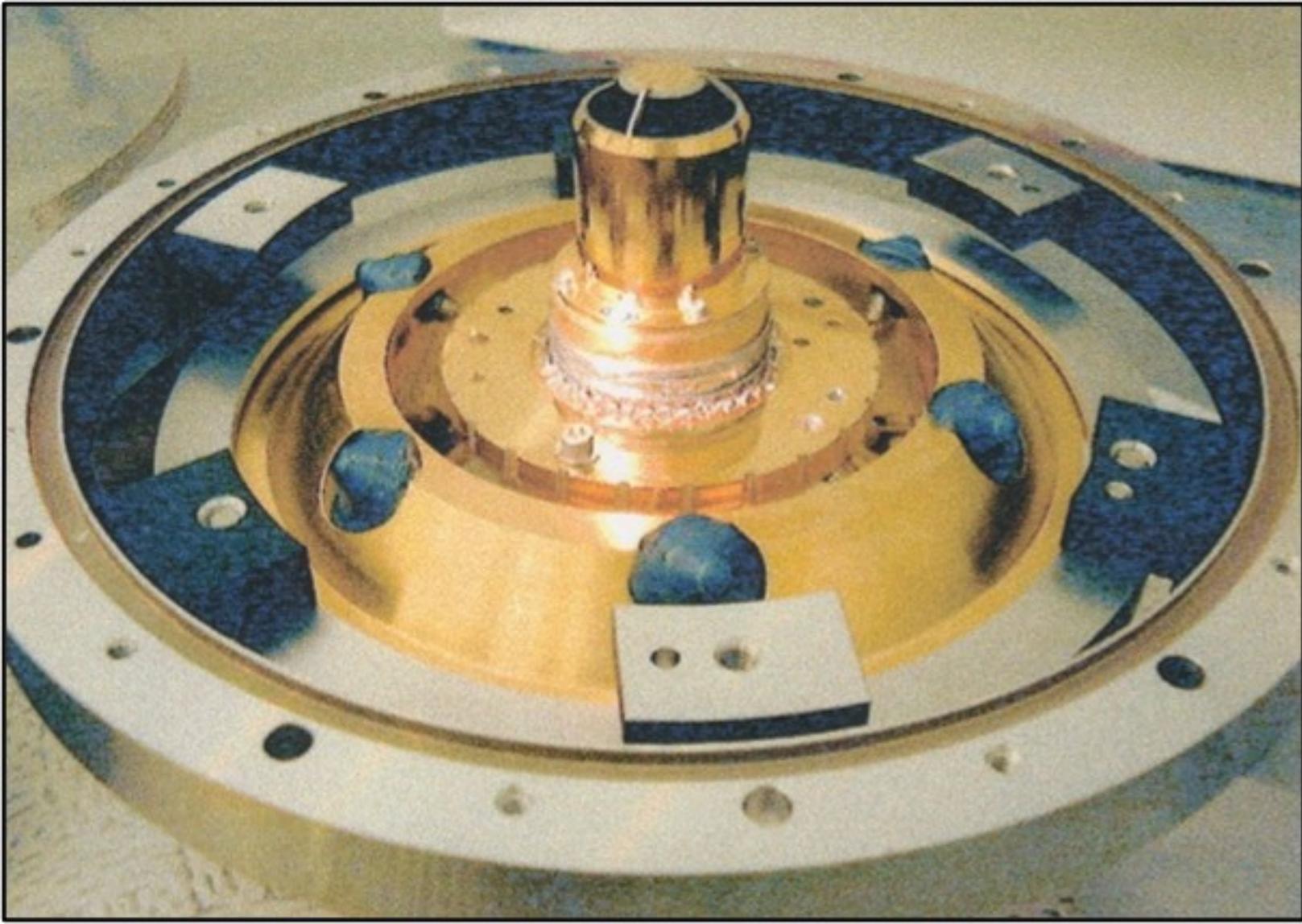


Figure 23.

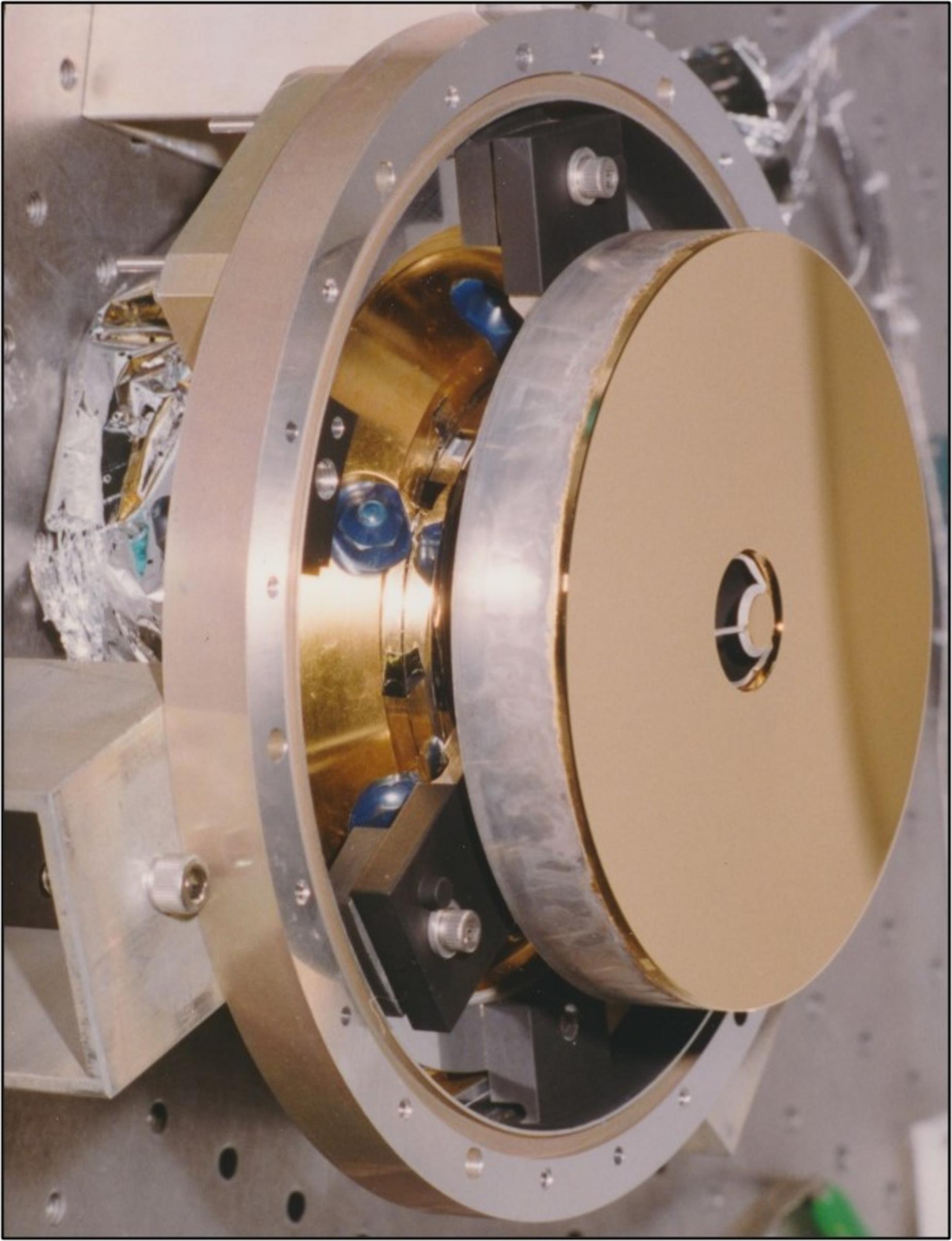


Figure 24.

