

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

2 **Instrument and Science Measurement Description**

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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. This paper presents a detailed  
74 technical description of the SABER instrument including major subsystems of the instrument and  
75 technical performance parameters. This paper comprehensively describes the instrument and its  
76 components and provides final instrument design and performance parameters. The motivation for  
77 this paper is to document this information permanently for future reference. The Space Dynamics  
78 Laboratory (SDL) of Utah State University designed, fabricated, and calibrated the SABER  
79 instrument in close collaboration with NASA Langley Research Center, Hampton University, and  
80 Global Atmospheric Technologies and Science (GATS).

81 **Plain Language Summary**

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

93 **Key Points**

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

100

101

102 **1. Introduction**

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

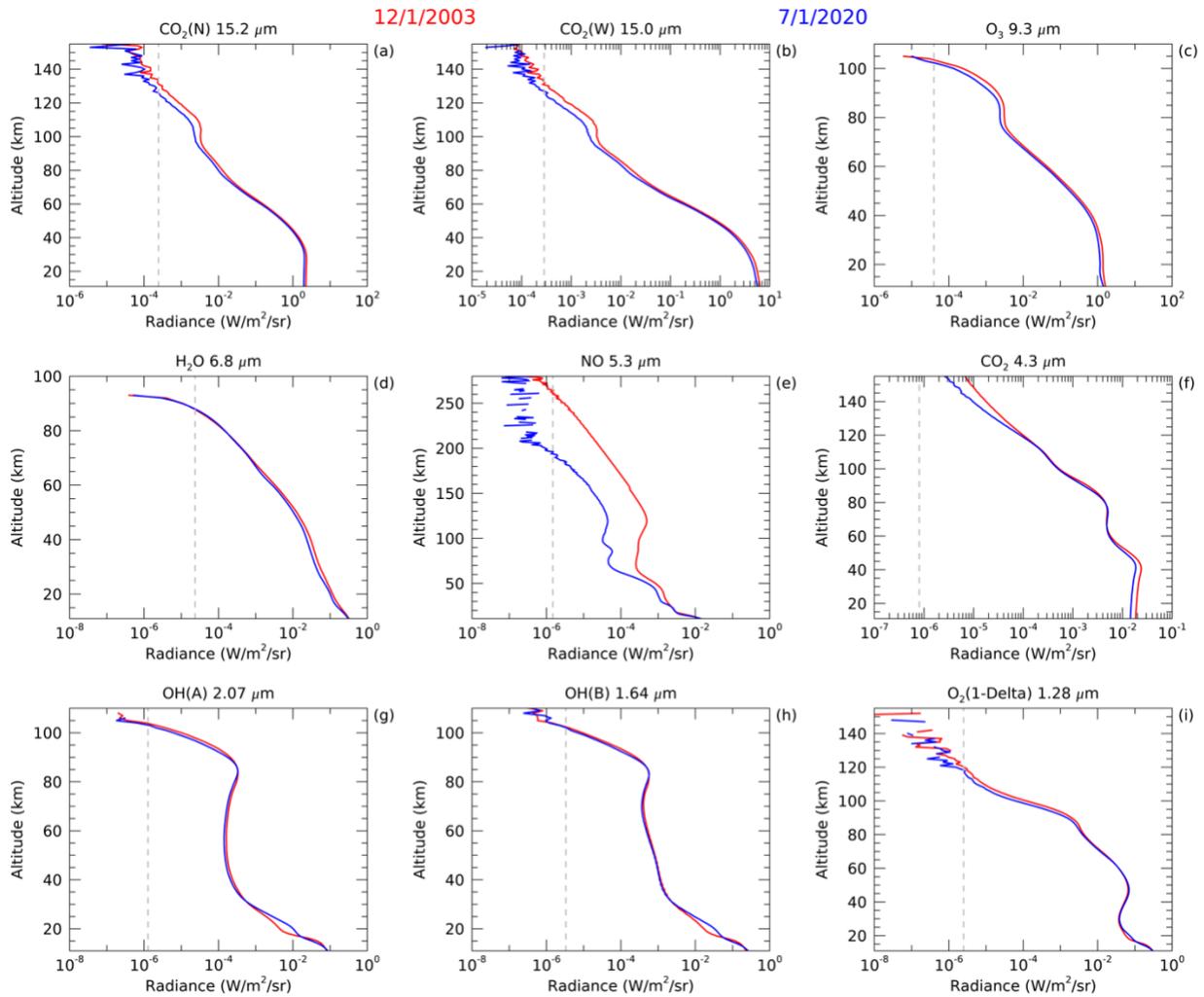
125 observations of the geospace environment are critical as this region is now undergoing long-term  
126 change due to increasing carbon dioxide (*Mlynczak et al., 2021, 2023*).

127         The SABER experiment was developed to conduct a comprehensive investigation into the  
128 thermal structure and energy balance of the MLT. The major elements of the energy budget are  
129 heating due to the absorption of solar radiation; heating due to exothermic chemical reactions that  
130 ultimately degrade much of the solar energy to heat; and infrared radiative cooling. *Mlynczak and*  
131 *Solomon* (1993) discuss in detail the entire chain of solar energy deposition, airglow (non-cooling)  
132 radiative losses, and heating through exothermic chemical reactions. Observations of kinetic  
133 temperature (T), ozone (O<sub>3</sub>), water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), nitric oxide (NO), atomic  
134 oxygen (O), and atomic hydrogen (H) are required to fully characterize the radiative energy budget  
135 of the MLT (*Mlynczak, 1996; 1997*). From these measurements the vertical profiles of the rates of  
136 radiative heating and cooling and rates of heating due to exothermic chemical reactions may be  
137 derived. Every day, SABER provides approximately 1,400 profiles each of temperature, minor  
138 constituents (O<sub>3</sub>, H<sub>2</sub>O, CO<sub>2</sub>, O, H), and more than 30 individual rates of radiative heating, radiative  
139 cooling, and rates of heating due to exothermic chemical reactions.

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

146         SABER's success is due to the excellent quality of the infrared limb radiances that it  
147 measures. As mentioned earlier, approximately 1,400 profiles of infrared limb radiance (units of

148  $\text{W m}^{-2} \text{sr}^{-1}$ ), per each of the 10 channels, are measured daily, resulting in over 100 million  
149 individual limb radiance profiles measured to date by SABER. Figure 1 illustrates the remarkable  
150 radiometric performance of the SABER instrument. Shown in this figure are orbit-average limb  
151 radiance profiles as a function of tangent altitude in each of the 10 SABER channels (described  
152 below in more detail). The red profiles are data taken approximately two years after launch in 2003  
153 during conditions near the maximum of the 11-year solar cycle. The blue profiles are taken 16.5  
154 years later during solar minimum conditions. The vertical dashed line in each figure marks the  
155 noise equivalent radiance (NER) value in each channel. The NER measured during ground  
156 calibration of SABER are listed later in Section 3.1 in Table 2. The altitude at which the NER line  
157 intersects the radiance profile is where the signal-to-noise is equal to unity. SABER routinely  
158 observes limb radiance to a minimum upper limit of 100 km and to above 270 km in the nitric  
159 oxide (NO) channel during solar maximum conditions.



160

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

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*

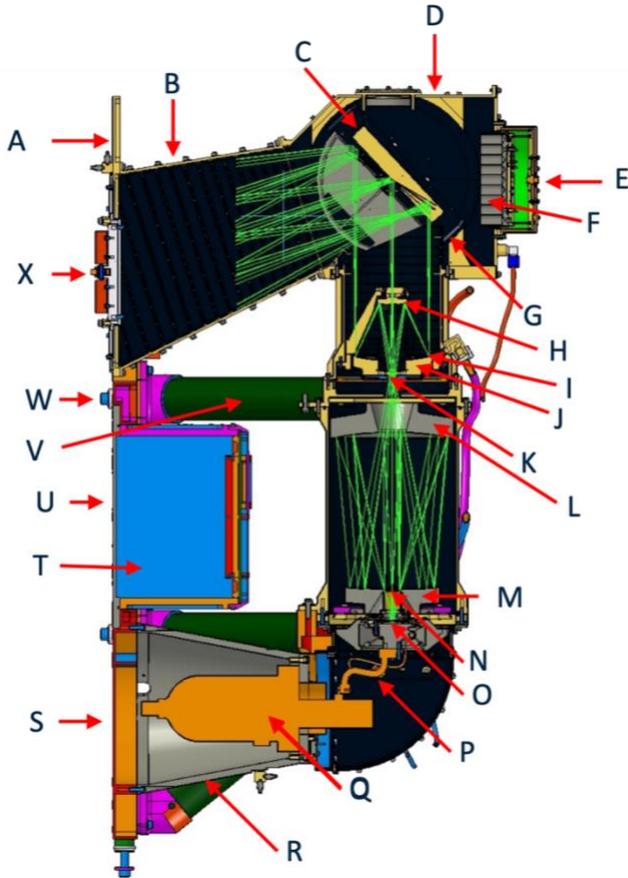
170 al., 2020) and that has lasted well beyond the two-year lifetime envisioned for the TIMED mission.  
171 The design and initial performance of SABER is described by *Brown et al.* (2006). The calibration  
172 of SABER is described by *Tansock et al.* [2003]. This present paper describes the instrument 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 CO<sub>2</sub>, O<sub>3</sub>, H<sub>2</sub>O, OH, NO, and O<sub>2</sub>(<sup>1</sup>Δ). 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.

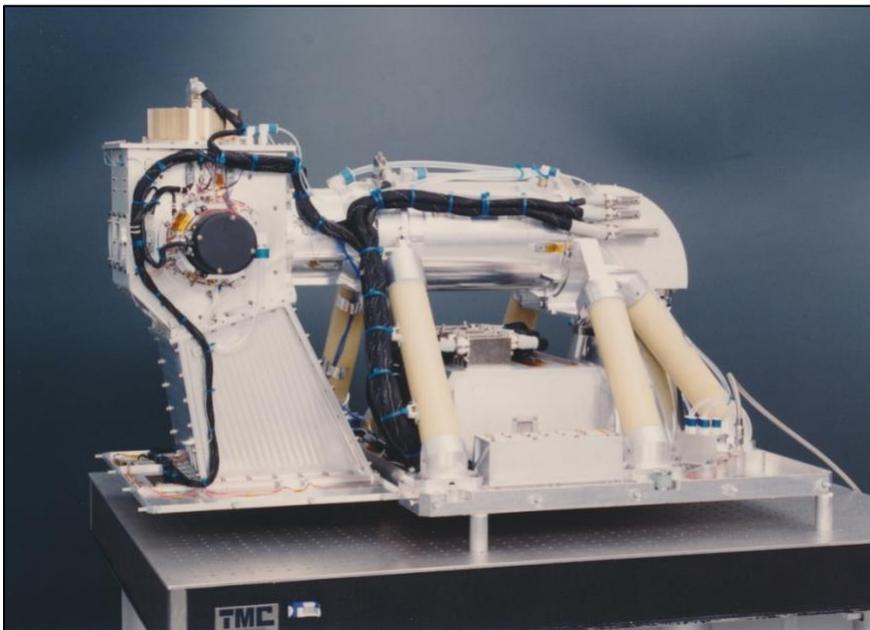


213  
214 **Figure 3.** The SABER instrument installed in the TIMED spacecraft.

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

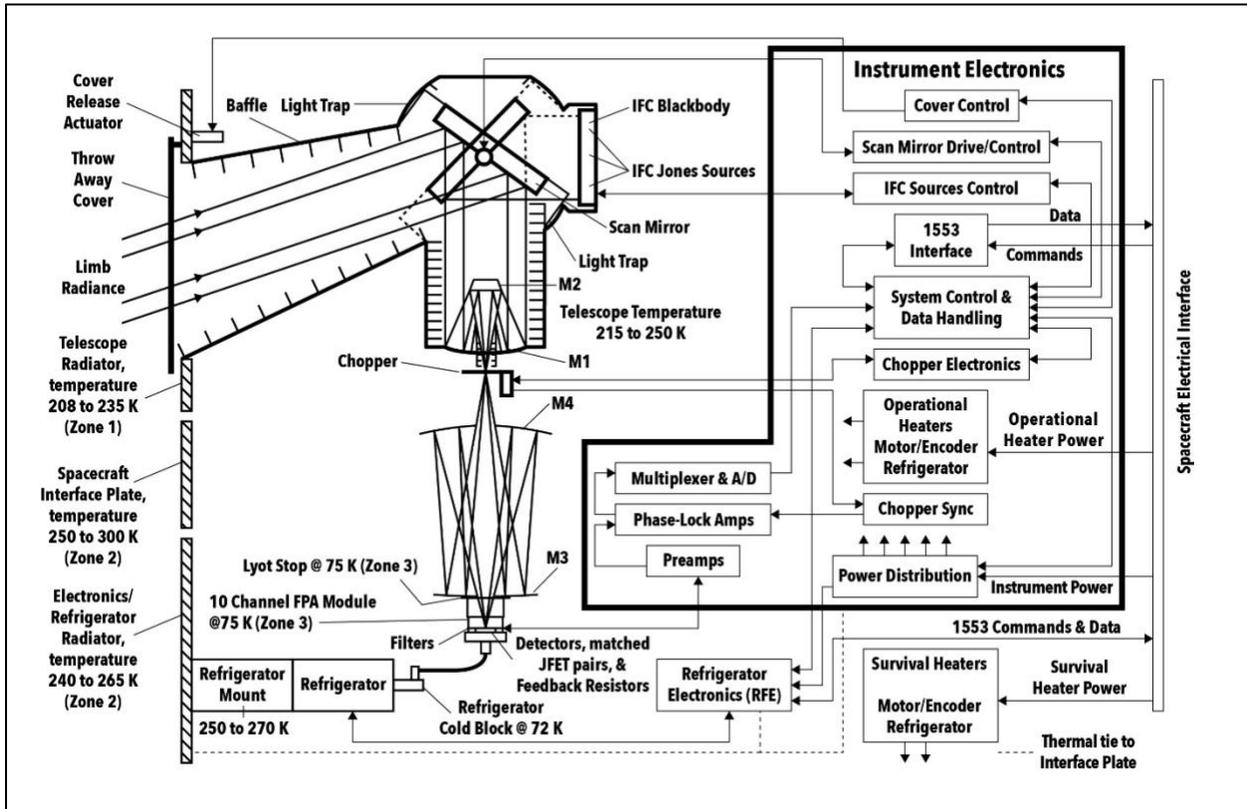
219 the view in Figure 2. MLI blanketing details are described later in Section 2.1.1, SABER Purge  
220 and Vent System. The long G-10 fiberglass legs (the tan colored struts in Figure 4) thermally  
221 isolate the optics (contained in the cylindrical-shaped tube) from the SABER/spacecraft interface  
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

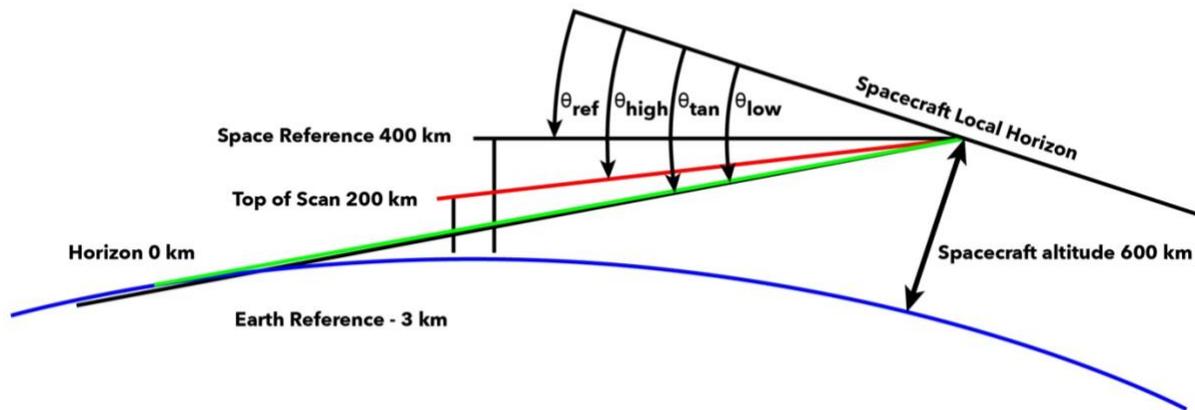
270 described later in this section, and additional descriptions of its components are given in the  
271 component section of this paper.

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 horizontal as shown schematically in Figure 6.

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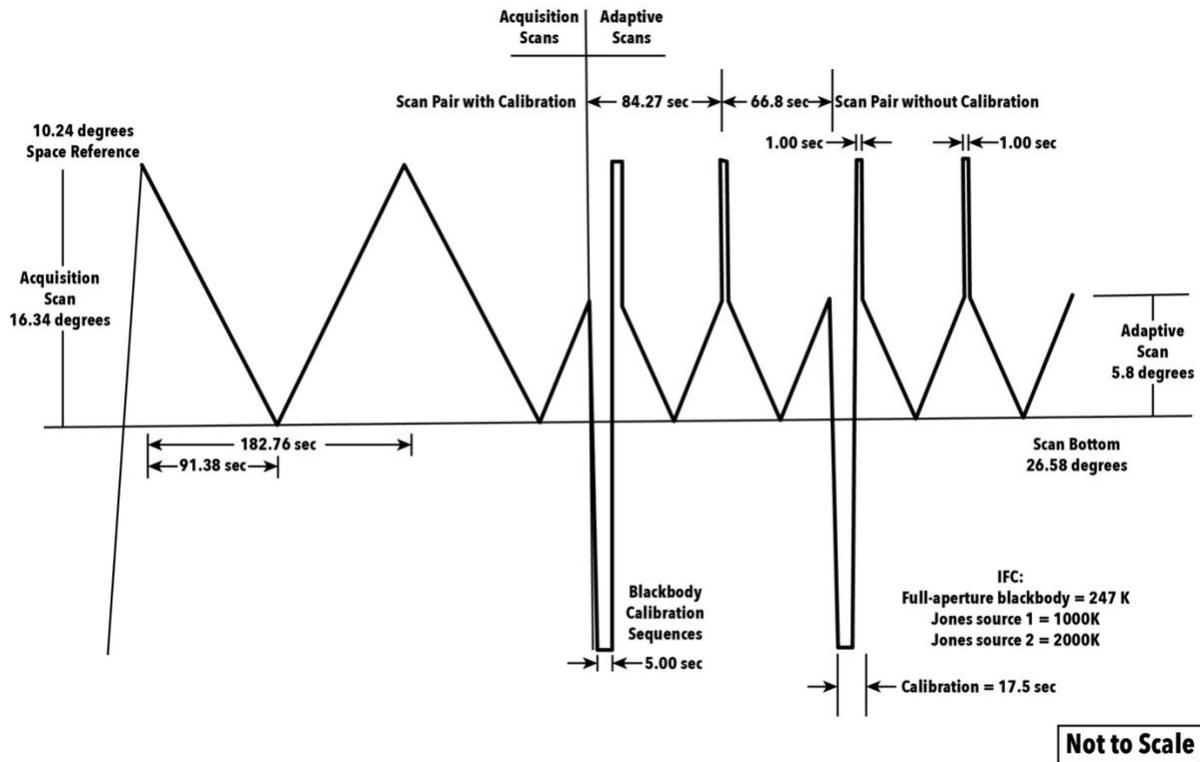
290 **Figure 6.** Schematic sketch defining SABER scan angles relative to the spacecraft local horizon.

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 CO<sub>2</sub> (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 CO<sub>2</sub>

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.

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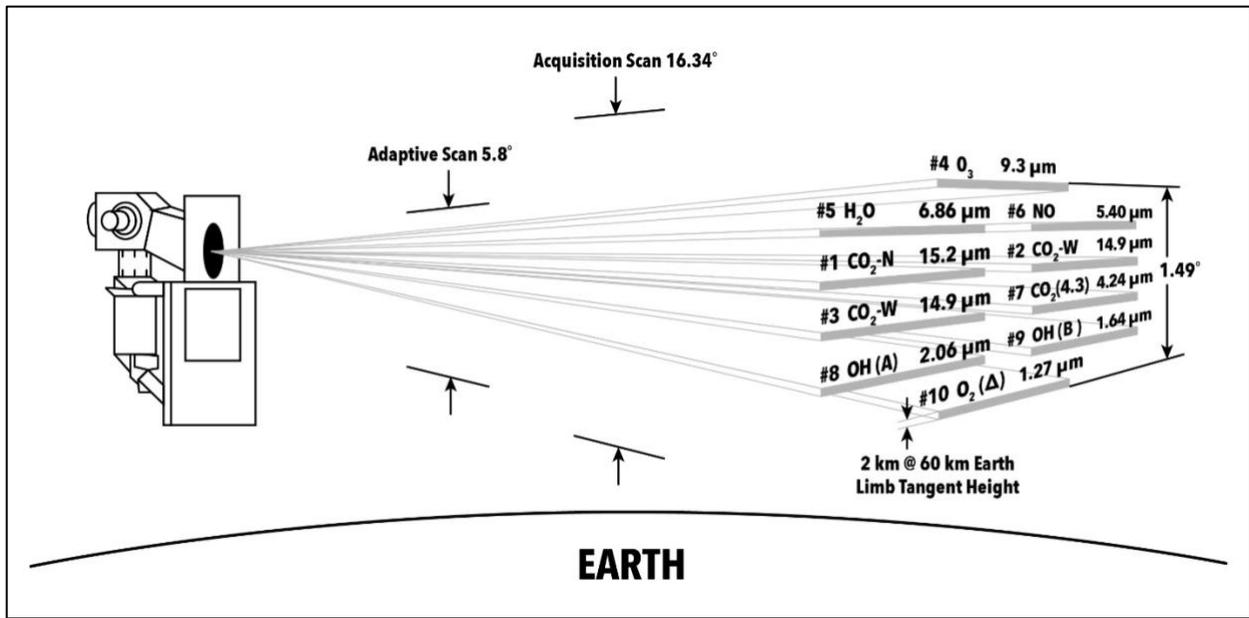


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310 **Figure 7.** SABER Earth limb scan sequence.

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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.

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319 2.1.1 SABER Purge and Vent System

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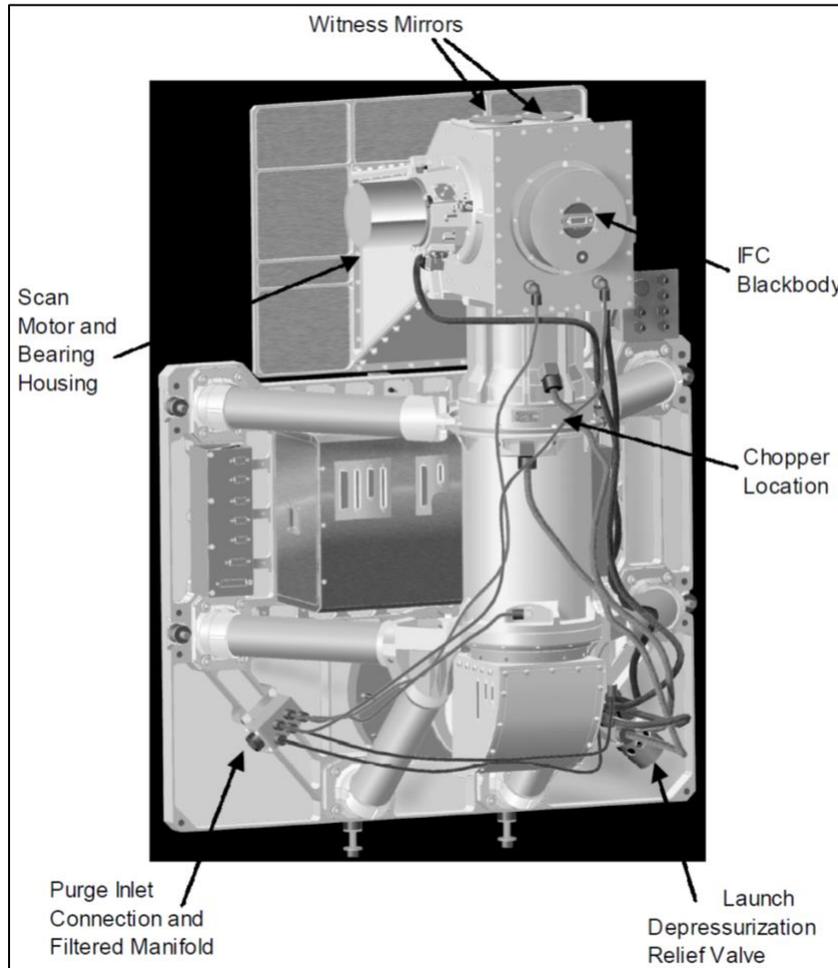
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To reduce vulnerability to water outgassing and to control particulate redistribution and contamination within the FPA (which is not hermetically sealed) SABER was designed with an optimized purge and vent system (Dyer *et al.*, 2002) as shown in Figure 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 FPA. 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 manifold includes

332 a 5- $\mu\text{m}$  particle filter and for each purge fitting, the telescope uses a sintered metal gas snubber  
333 filter disk to provide additional filtering and eliminate stray light leaks. Once installed, the purge  
334 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 N<sub>2</sub> 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 ( $\mu\text{m}$ ) and reciprocal wavelength or wavenumbers ( $\text{cm}^{-1}$ ). 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  $\text{CO}_2$  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 ( $\text{O}_3$ ), water vapor ( $\text{H}_2\text{O}$ ), nitric oxide (NO). Channel 7 measures infrared  
 375 radiation from  $\text{CO}_2$  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
		( $\text{cm}^{-1}$ )	( $\mu\text{m}$ )	( $\text{cm}^{-1}$ )	( $\mu\text{m}$ )	( $\text{cm}^{-1}$ )	( $\mu\text{m}$ )	
1	$\text{CO}_2$ (N)	674	14.837	698	14.327	649	15.408	< 5E-04
2	$\text{CO}_2$ (W)	672	14.881	764	13.089	581	17.212	< 1E-04
3	$\text{CO}_2$ (W)	672	14.881	763	13.106	580	17.241	< 1E-04
4	$\text{O}_3$	1080	9.259	1146	8.726	1013	9.872	< 3E-04
5	$\text{H}_2\text{O}$	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	$\text{CO}_2$	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	$\text{O}_2$	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		<sup>1,2</sup> NER (W/m <sup>2</sup> sr <sup>-1</sup> )	300 K Radiance (W/m <sup>2</sup> sr <sup>-1</sup> )	Modeled Earth & Atmosphere Radiance (W/m <sup>2</sup> sr <sup>-1</sup> )	<sup>3</sup> 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 <sub>2</sub> (N)	2.45E-04	5.63E+00	2.70E+00	2.3E+04	21.1	21.1	1.0	4080	174
2	CO <sub>2</sub> (W)	2.84E-04	2.44E+01	9.98E+00	8.6E+04	60.0	7.7	1.0	4080	470
3	CO <sub>2</sub> (W)	3.32E-04	2.44E+01	9.98E+00	7.3E+04	68.6	8.3	1.0	4080	442
4	O <sub>3</sub>	3.96E-05	9.49E+00	5.67E+00	2.4E+05	183.4	13.6	1.0	4080	269
5	H <sub>2</sub> 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 <sub>2</sub>	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 <sub>2</sub>	2.49E-06	4.64E-11	2.15E+00	8.7E+05	376.3	19.6	1.0	4080	187

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

398 <sup>2</sup>NER values are from the ground calibration.

399 <sup>3</sup>Dynamic 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

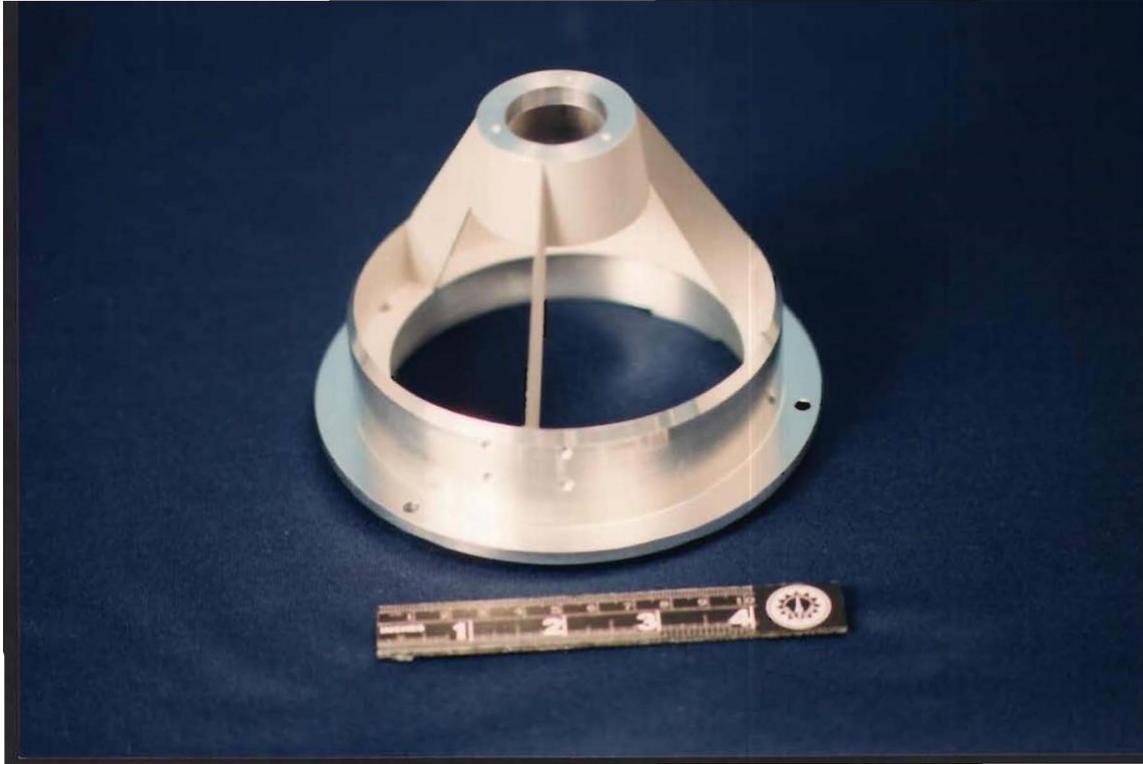
403 **3.2 SABER Optical Parameters**

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 <sup>2</sup>
Entrance Pupil Area	49,309	cm <sup>2</sup>
Solid Angle $\Omega$	0.115	sr
Chopper Modulation Factor	0.446	N/A
Chopping Frequency	1000	Hz
Limb Scan Mirror Jitter ( $1\sigma$ )	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,  $\Omega$ , 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 ( $\theta_1$ ), and half angle at detector of inner  
 421 aperture edge image ( $\theta_2$ ), 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 ( $\tau_a$ ). The value of the solid angle  
 423 for all channels is the same. The solid angle was computed using the follow equation:

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

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  $\tau_o$  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 ( $\tau_o$ )
No	Species	(km)	( $\text{cm}^2\text{sr}$ )	(N/A)
1	CO <sub>2</sub> (N)	1.68	2.92E-04	0.673
2	CO <sub>2</sub> (W)	1.59	2.91E-04	0.820
3	CO <sub>2</sub> (W)	1.49	2.92E-04	0.820
4	O <sub>3</sub>	1.97	3.38E-04	0.796
5	H <sub>2</sub> O	1.73	3.41E-04	0.782
6	NO	1.97	3.39E-04	0.641
7	CO <sub>2</sub>	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 <sub>2</sub>	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  $\beta$  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 (NEBW)	4.687	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
$\Delta T$ 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 <sup>2</sup>
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 <sup>2</sup>
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 CO<sub>2</sub> (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  $\theta$  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 CO<sub>2</sub> (W) channel given above, the 45 km tangent height is approximately 1 degree in angle

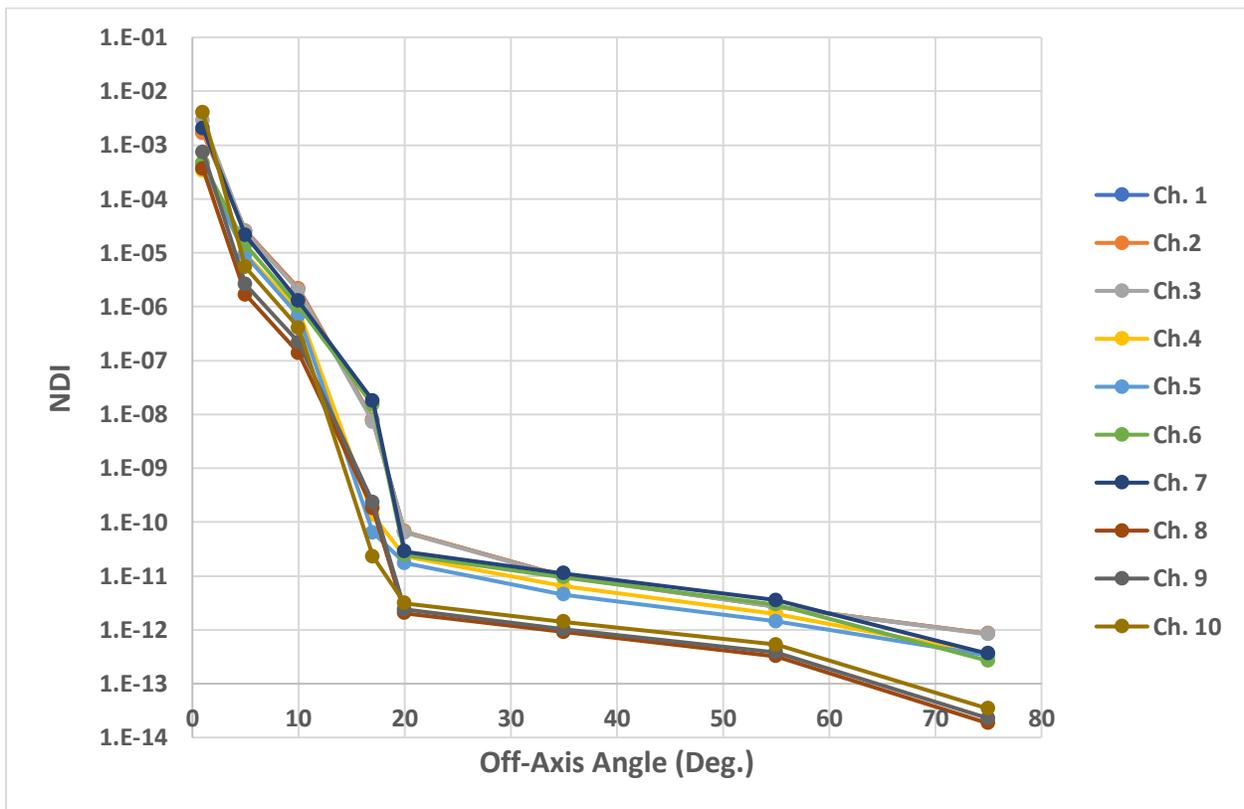
496 below the 80 km tangent height from SABER's orbit altitude. Table 7 shows an NDI of 0.17% for  
 497 the CO<sub>2</sub>(W) channel at 1 degree, illustrating the exceptional off-axis rejection of the instrument.

498

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

#	Channel	Center Wave-length (mm)	NER (W/[cm <sup>2</sup> sr])	Tangent Height h <sub>tan</sub> (km)	NDI							
					Off-Axis Angle (degrees)							
	Species				1	5	10	17	20	35	55	75
1	CO <sub>2</sub> (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 <sub>2</sub> (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 <sub>2</sub> (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 <sub>3</sub>	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 <sub>2</sub> 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 <sub>2</sub>	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 <sub>2</sub>	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:

$$507 \quad NRR = \frac{2A_d}{A_{EP}\Omega_{FOV}} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} NDI(\theta) radiance(h(\theta, \varphi)) \sin \theta \, d\theta \, d\varphi \quad (5)$$

508 where  $A_d$  is area of detector,  $A_{EP}$  is area of baffle entrance port,  $\Omega_{FOV}$  is solid angle of detector,  
 509  $NDI(\theta)$  is normalized detector irradiance as a function of the polar angle from the baffle axis,  
 510  $radiance(h(\theta, \varphi))$  is the radiance as a function of tangent height, which is in turn a function of  
 511 the polar and azimuth angles  $\theta$  and  $\varphi$ .

512 Two figures of merit are developed to assess SABER’s off-axis rejection performance. The  
 513 first is the ratio of the NRR to NER reported earlier in Table 2 and listed in Table 8 in the column  
 514 labeled (NRR/NER). This column demonstrates that the SABER non-rejected radiance at the  
 515 indicated tangent altitudes is substantially less than the instrument noise, sometimes by several  
 516 orders of magnitude.

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

523  
 524  
 525  
 526

527 **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 <sub>2</sub> (N)	14.837	2.45E-04	70	5.113E-05	2.090E-01	2.326E-02	455
2	CO <sub>2</sub> (W)	14.881	2.84E-04	70	1.854E-04	6.530E-01	3.562E-02	192
3	CO <sub>2</sub> (W)	14.881	3.32E-04	70	2.980E-04	8.980E-01	3.562E-02	120
4	O <sub>3</sub>	9.259	3.96E-05	70	1.318E-09	3.327E-05	2.645E-04	200784
5	H <sub>2</sub> 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 <sub>2</sub>	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 <sub>2</sub>	1.276	2.49E-06	70	1.481E-08	5.948E-03	4.095E-04	27649

528

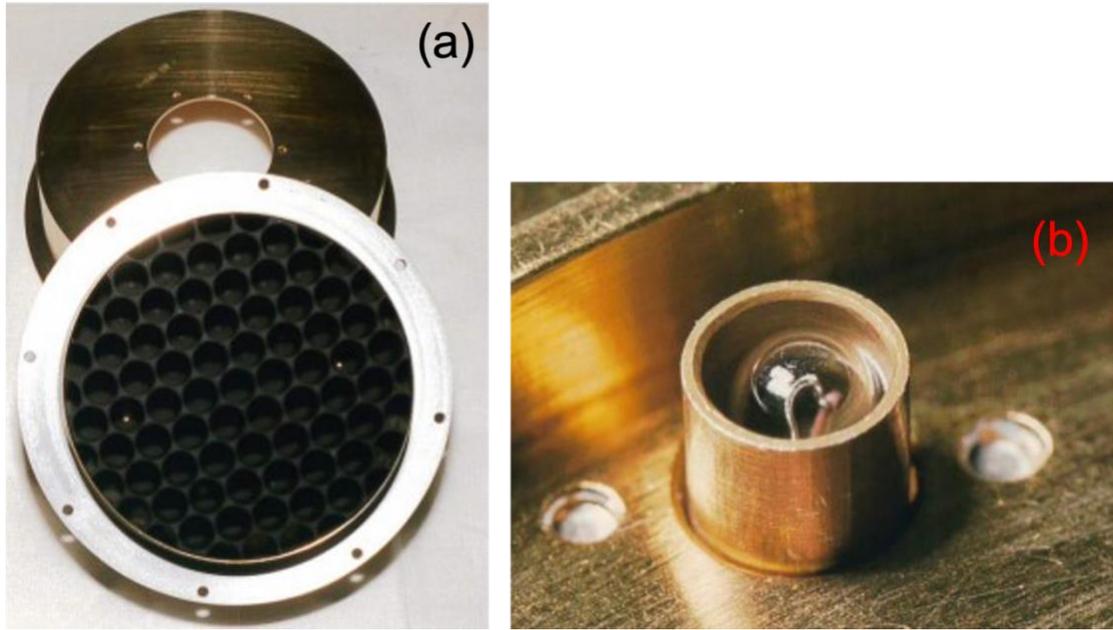
529 **4. Major Components of the SABER Instrument**

530 **4.1 SABER In-Flight Calibrator**

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

538

539



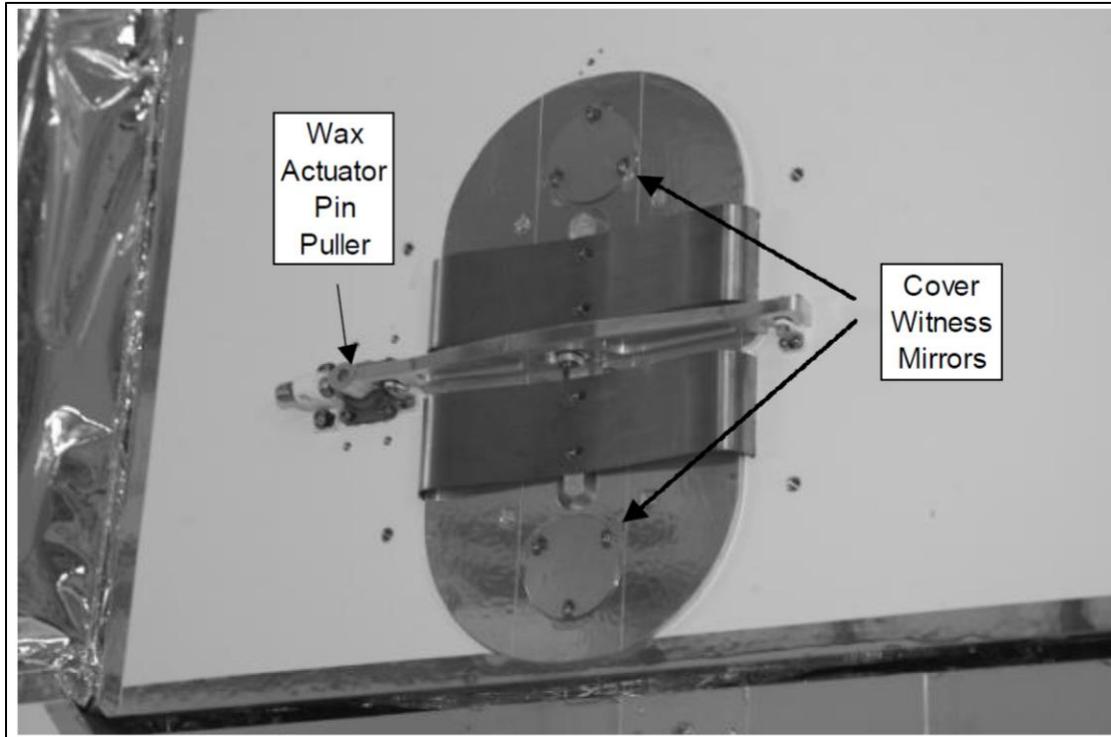
540

541 **Figure 12.** (a, left image) Full aperture blackbody, (b, right image) one of three tungsten-filament  
542 Jones sources before being embedded in the full-aperture blackbody.

543

#### 544 ***4.2 Entrance Aperture Cover***

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



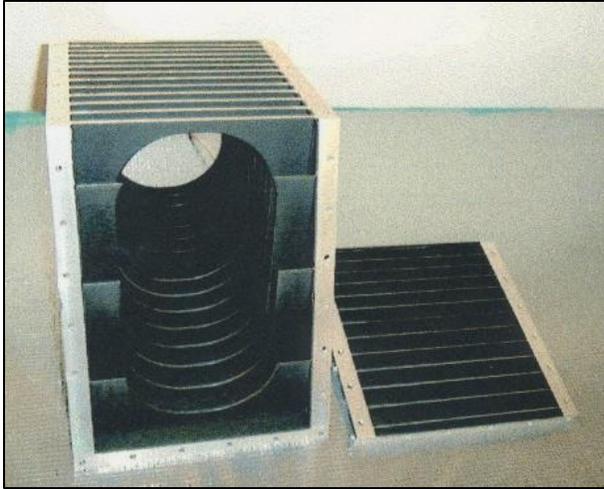
555

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

557

#### 558 **4.3 Fore-Optics Baffle Assemblies**

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



565

566 **Figure 14.** Fore-optics baffle assembly.

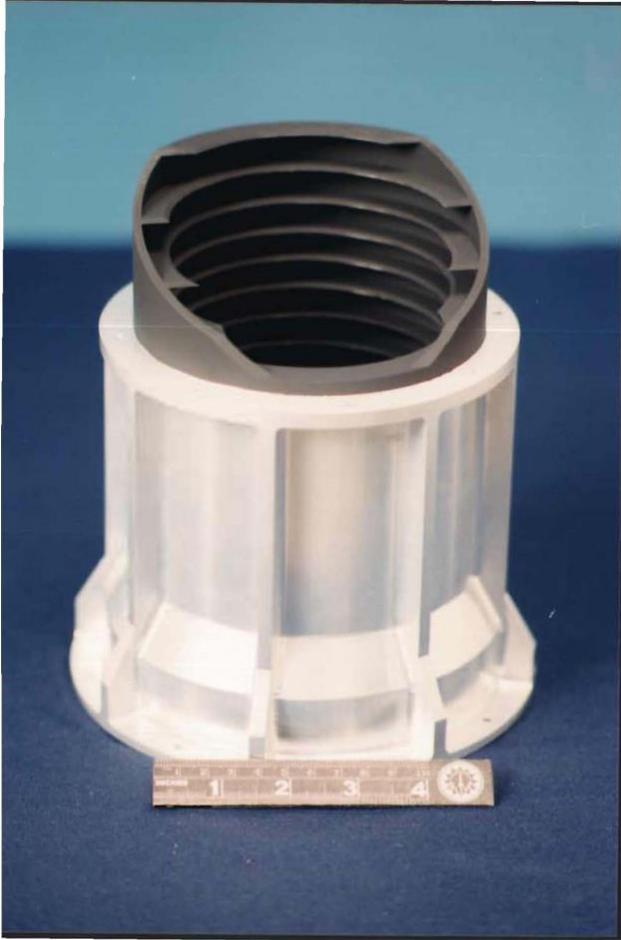
567

568           The baffle surrounding the Ritchey-Chrétien telescope is a cylindrical baffle with its  
569 entrance port at an angle to prevent it from blocking needed rays on their way to the scan mirror.

570 This baffle is shown below in Figure 15 and surrounds mirrors M1 and M2 (Items H and J in  
571 Figure 2). A schematic drawing of this baffle can be seen in Figure 5, which also shows a schematic

572 sketch of the fore-optics baffle.

573



574

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

576

#### 577 ***4.4 Encoder/Motor Assembly***

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

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

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

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

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

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

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

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

586 past the operational rotation limits. One of the most important pointing parameters for mapping  
 587 the radiance versus tangent height is the encoder accuracy of 25  $\mu$ radians rms (5.2 arc seconds).

588

589 **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 <sup>2</sup>
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 $\Omega$ , pF
Motor Constant	4.623	kg-mm/vw
Encoder Outputs	Quadrature w/zero ref	N/A
Encoder Cycles per Channel/Revolution	262,144 (2 <sup>18</sup> )	N/A
Encoder Accuracy (over 360° rotation)	25	$\mu$ 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
$\Delta$ T at Encoder Mount to Baffle	5	K
Design Life Total Scan Cycles	3.8E6 (3 years)	N/A

590

591 **4.5 Mirrors**

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

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

612 4.5.1 Scan Mirror

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

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

630

631 **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 $\mu\text{m}$ 1.12E-2/ $\theta^{2.88}$ @ 13.39 $\mu\text{m}$ 6.14E-4/ $\theta^{2.06}$ @ 1.2 $\mu\text{m}$	steradian <sup>-1</sup>
$\Delta T$ across mirror	$\leq 2$	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

632

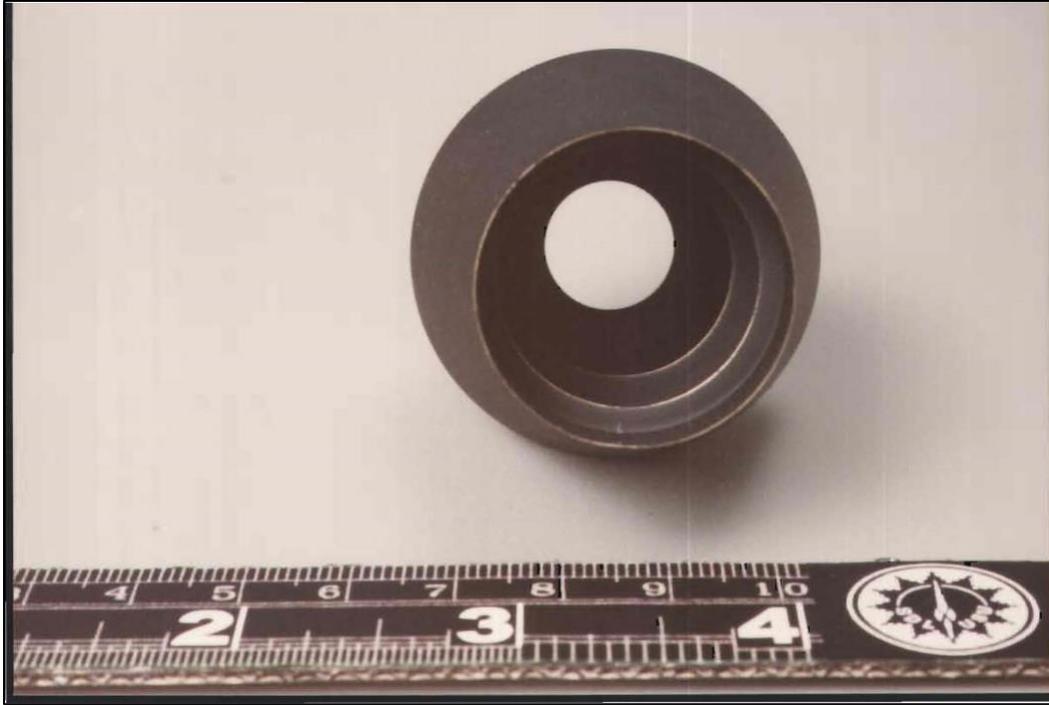
633 4.5.2 Primary Mirror

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

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



647  
648 **Figure 16.** SABER Primary mirror M1.  
649



650

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

652

653 **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 ( $\theta$ is the angle off specular expressed in degrees)	$9.73E-5/\theta^{1.83}$ @ 10.6 $\mu\text{m}$ $2.42E-3/\theta^{2.88}$ @ 3.39 $\mu\text{m}$ $2.42E-3/\theta^{2.03}$ @ 1.2 $\mu\text{m}$	steradian <sup>-1</sup>
Reflectance	0.98	N/A
$\Delta T$ across mirror	$\leq 2$	K
Mass	0.39	kg

654

655 4.5.3 Secondary Mirror, Secondary-Mirror Spider, and Secondary-Mirror Baffle

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

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

663         The assembly procedure to install the secondary mirror was to first lay a nominal thickness  
664 ring shim on the top of the support and then insert secondary mirror mounting feet through the  
665 hole in the top of the support, bolt these feet to a mounting plate, and finally bolt the mounting  
666 plate to the top of the support. The focus location and image quality of the M1-M2 pair was  
667 checked interferometrically. The thickness of the shim and the decenter of the secondary mirror  
668 relative to the primary mirror was iterated until the focus location and image quality requirements  
669 were satisfactory.

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

677

678

679

680

681

682 **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 ( $\theta$ is the angle off specular expressed in degrees)	2.44E-3/ $\theta^{3.01}$ @ 10.6 $\mu\text{m}$ 1.86E-3/ $\theta^{2.881}$ @ 3.39 $\mu\text{m}$ 6.14E-4/ $\theta^{2.06}$ @ 1.2 $\mu\text{m}$	steradian <sup>-1</sup>
Reflectance	0.98	N/A
Mass (measured)	0.38	kg

683

684 4.5.4 Tertiary and Quaternary Mirrors

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

696

697

698

699

700 **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	-60.08293 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

701

702 **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

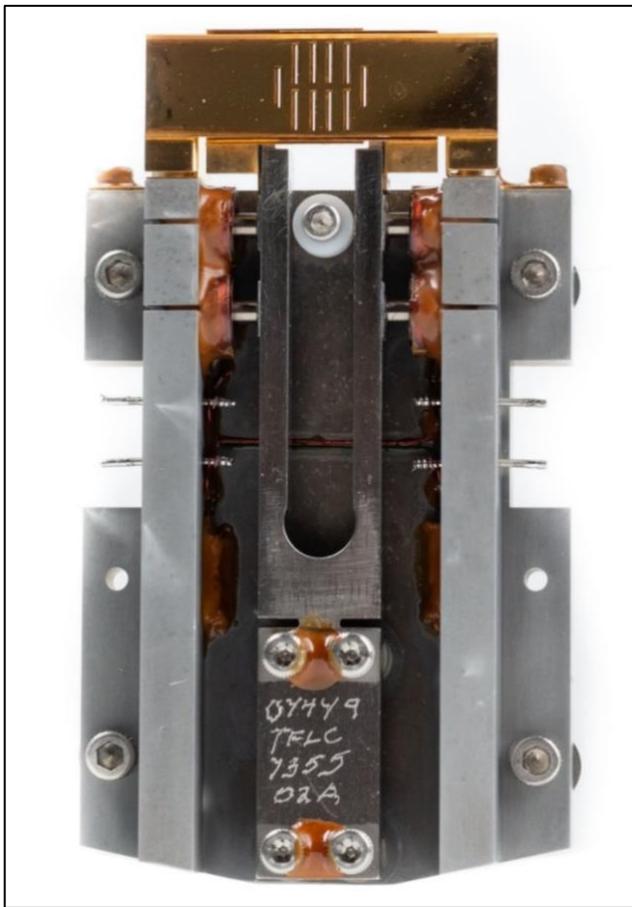
703

704 **4.6 SABER Optical Chopper**

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

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

722



723

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

725

726 **4.7 SABER Focal Plane Array (FPA)**

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

733 Photoconductive (PC) detectors are used for the long-wavelength detector channels  
 734 (channels 1 through 5) and photovoltaic (PV) for the short-wavelength detector channels. Table  
 735 15 and Table 16 show the parameter values for the PC and PV detectors, respectively. All  
 736 parameter values are at the 1000 Hz SABER chopping frequency. D\* is the detector specific  
 737 detectivity.

738 **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 <sup>2</sup> √Hz/W)
1	CO <sub>2</sub> (N)	HgCdTe	249	699	1.5	1.6	12.07	1.9E+04	7.53E+10	
2	CO <sub>2</sub> (W)	HgCdTe	233	606	1.5	1.4	11.57	1.4E+04	5.76E+10	
3	CO <sub>2</sub> (W)	HgCdTe	269	681	1.5	1.5	13.1	1.5E+04	5.44E+10	
4	O <sub>3</sub>	HgCdTe	530	1274	1.0	1.0	7.46	1.4E+05	9.19E+11	
5	H <sub>2</sub> O	HgCdTe	1209	2563	1.0	1.0	9.56	1.2E+05	6.50E+11	

739

740 **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 <sup>2</sup> √Hz/W)
6	NO	InSb	6.28E+07	3.2	0.69	3.69	1.8E+13
7	CO <sub>2</sub>	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 <sub>2</sub>	InGaAs	9.56E+07	3.3	0.21	0.92	2.3E+13

741

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

748 **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 ( $\mu\text{m}$ )
	5% Absolute		Slope	5% Absolute		Slope			
	( $\text{cm}^{-1}$ )	( $\mu\text{m}$ )	(%)	( $\text{cm}^{-1}$ )	( $\mu\text{m}$ )	(%)			
1	698.2	14.323	1.27	648.2	15.427	1.13	74.4	$\leq 0.05$	22.4
2	760.2	13.154	1.61	577.45	17.319	1.77	90.7	$\leq 0.03$	24.4
3	606.2	13.154	1.61	577.45	17.319	1.77	90.7	$\leq 0.03$	24.4
4	1144.8	8.735	1.38	1012.9	9.873	1.03	88.1	$\leq 0.02$	15.5
5	1565.0	6.390	1.4	1369.1	7.304	1.00	86.5	$\leq 0.02$	12.5
6	1941.1	5.152	0.92	1864.4	5.364	1.47	70.9	$\leq 0.01$	10.0
7	2387.9	4.188	0.28	2303.4	4.341	0.51	70.6	$\leq 0.01$	10.0
8	5153.4	1.940	1.04	4511.0	2.217	0.88	85.9	$\leq 0.01$	10.0
9	6420.5	1.558	0.99	5750.2	1.739	0.98	83.7	$\leq 0.01$	10.0
10	7965.2	1.255	1.06	7710.6	1.297	0.69	60.7	$\leq 0.01$	5.0

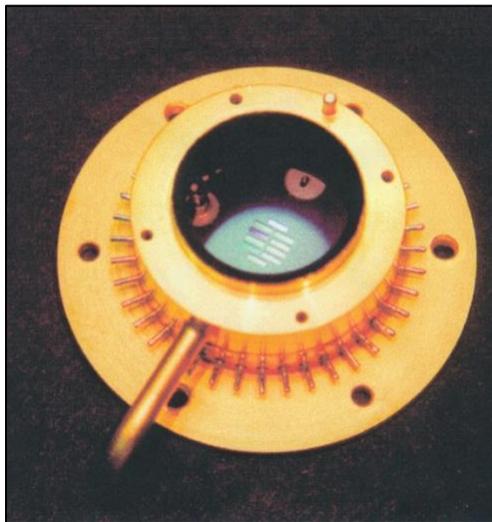
749  
750 Figure 19 shows the detector ceramic circuit board populated with detectors, JFETs,  
751 feedback resistors, and feedback capacitors. The height of each detector was adjusted to correct  
752 for the chromatic aberration caused by the filters. Electrical connections to the detector assembly  
753 were made by soldering shielded stainless steel wires to the radially protruding pins. Shielded  
754 stainless steel wires were used to minimize thermal conduction from the warm electronics to the  
755 detector assembly.



756

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

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

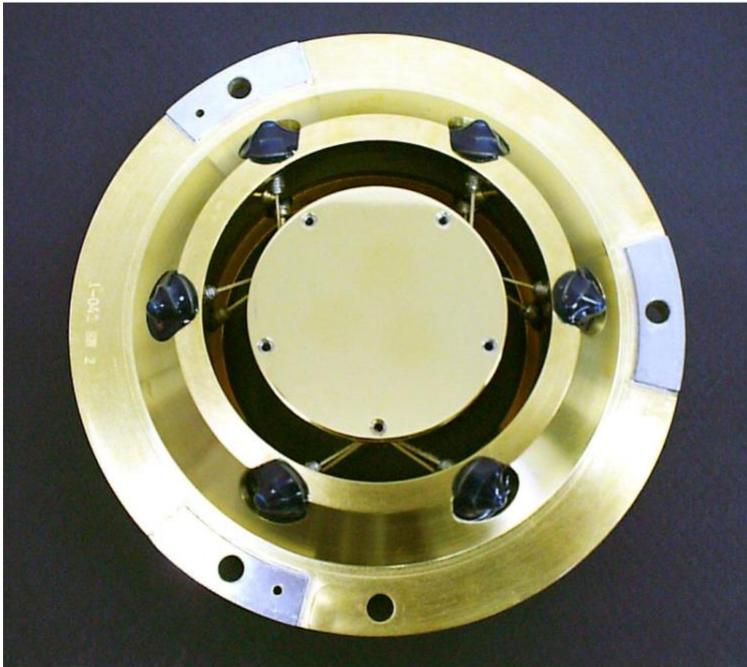


765

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

768 **4.8 SABER Fiber Support Technology (FiST)**

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



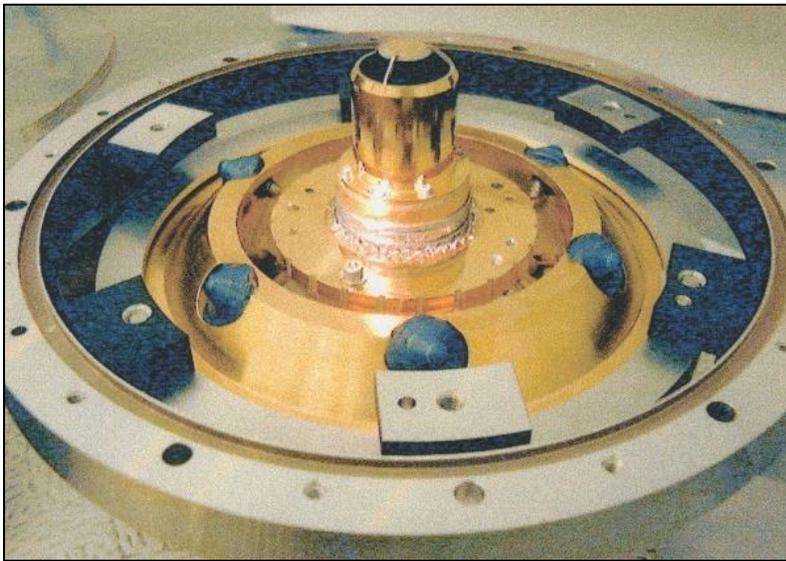
780

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

782

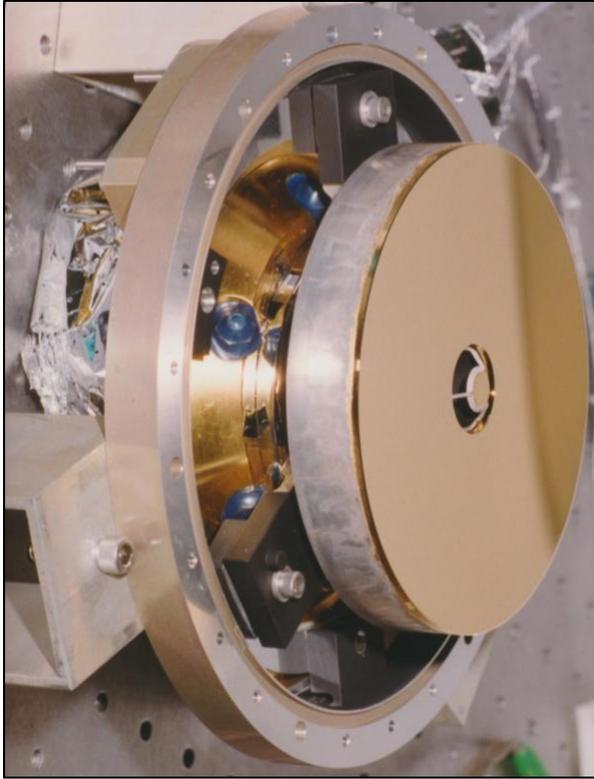
783 **4.9 SABER Lyot Stop**

784 The SABER Lyot Stop is shown mounted on the top of the FPA in Figure 22 and is shown  
785 as item N in Figure 2. It is a novel 3-dimensional design that blocks light scattered and diffracted  
786 from the edges of the aperture stop, the secondary mirror baffle, and the secondary mirror support  
787 struts. Diffracted and scattered light from the edges of the aperture stop, which is few mm in front  
788 of the primary mirror, is blocked by the outside edge of the circular Lyot stop opening that can be  
789 seen in Figure 22. Diffracted and scattered light from the edges of the secondary mirror baffle is  
790 blocked by the inner edge of the central obscuration of the Lyot stop. Diffracted and scattered light  
791 from the three secondary mirror struts is blocked by the Lyot stop struts. The SABER Lyot stop  
792 protrudes through the central hole of the tertiary mirror as can be seen in Figure 23.



793  
794 **Figure 22.** Lyot stop mounted to the top of the FPA

795



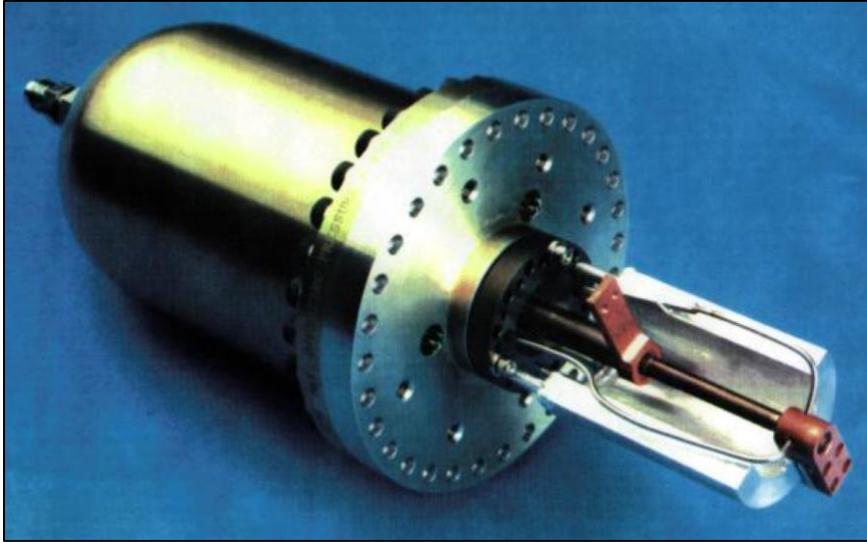
796

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

798

#### 799 **4.10 SABER Cryocooler**

800 Figure 24 shows the pulse-tube cryocooler used in SABER and developed by the TRW  
801 Corporation in the mid-1990s. At the time SABER was built, this cryocooler was known as a  
802 miniature cryocooler. The mass of this cryocooler head is  $2.014 \text{ kg} \pm 0.5 \text{ kg}$ , and the electronics  
803 mass is  $2.50 \text{ kg} \pm 0.25 \text{ kg}$ . This cooler has now been operating nearly continuously in space for  
804 over 21 years. The only time it has been turned off has been to enable evaporation of cryo-films  
805 that are deposited over time on the FPA, flex link and cooler cold tip due to outgassing of MLI on  
806 the outside of the SABER instrument, the other TIMED instruments, and the TIMED spacecraft.  
807 Before launch, this cryocooler was run for several months in a US Air Force testing laboratory.  
808 The approach to cooling SABER with this device is given in *Jensen et al. (1998)*.



809

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

811

#### 812 ***4.11 SABER Electronics***

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

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

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

832

833 **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
<b>Totals</b>		29.0	42.5	29.0	29.0	5.6	5.6

834

835 **Summary and Future Directions**

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

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

848         The mesosphere and lower thermosphere (MLT) region that has been comprehensively  
849 explored by SABER over the past 21-plus years is undergoing long-term change due to steadily  
850 increasing concentrations of carbon dioxide (*Mlynczak et al., 2022*). The MLT is the lower portion  
851 of ‘geospace,’ the region between approximately 60 km and 600 km altitude. All geospace is being  
852 influenced by the cooling effects of increasing carbon dioxide, as predicted over 30 years ago  
853 (*Roble and Dickinson, 1989; Cicerone, 1990*). To fully understand these changes, and especially  
854 to confront the likely economic and policy consequences of climate change in geospace, continued  
855 observations of the MLT and geospace are urgently needed. However, due to many factors, a gap  
856 in observations seems likely (*Mlynczak et al., 2021*).

857         Several years ago, SABER team members developed a design for a more compact version  
858 of the instrument that would preserve the optical and radiometric performance but would require  
859 substantially less mass, power, and volume to achieve. The resulting design, originally called the  
860 “Middle Atmosphere Sounder and Thermal Emission Radiometer (MASTER)” (*Mlynczak et al.,*  
861 2014) is now referred to as “SABER-II.” The SABER-II design requires one-half the mass and  
862 power and takes up one-third of the volume of the legacy SABER instrument now in orbit. The  
863 key factors enabling SABER-II are modern electronics and more efficient cryocoolers that require

864 significantly less power to operate. Less power translates into smaller radiator area to dissipate the  
865 heat generated and keep SABER’s telescope, focal plane, and radiators at their required  
866 temperatures. In addition, experience with SABER and further optical modeling enables  
867 substantial reduction and possible elimination of the large telescope baffle on the legacy SABER  
868 instrument without compromising the excellent off-axis stray light rejection of the SABER  
869 telescope. These several factors combine to significantly reduce the ‘footprint’ of the SABER-II  
870 instrument. A copy of the poster presentation describing the SABER-II (MASTER) instrument  
871 from the 2014 AGU Meeting is included as Supporting Information.

872           Finally, NASA Langley, Space Dynamics Laboratory, and the Johns Hopkins University  
873 Applied Physics Laboratory have conducted engineering design studies that showed SABER-II  
874 can be accommodated into commercially available small satellite buses with substantial margin on  
875 power and pointing capability. The SABER team has also been actively advocating for continuity  
876 of the ‘*geospace data record*’ (Mlynczak *et al.*, 2023) established by SABER in support of the  
877 upcoming Decadal Survey for NASA’s Heliophysics Division.

878

## 879 **Open Research**

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

886

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905

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**Figure 1.**

12/1/2003

7/1/2020

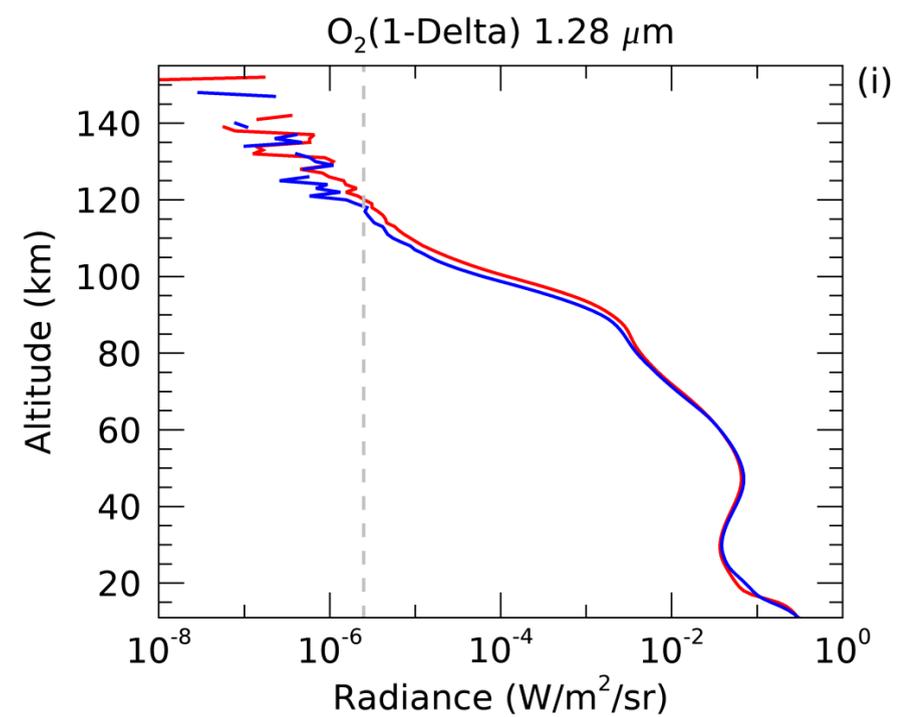
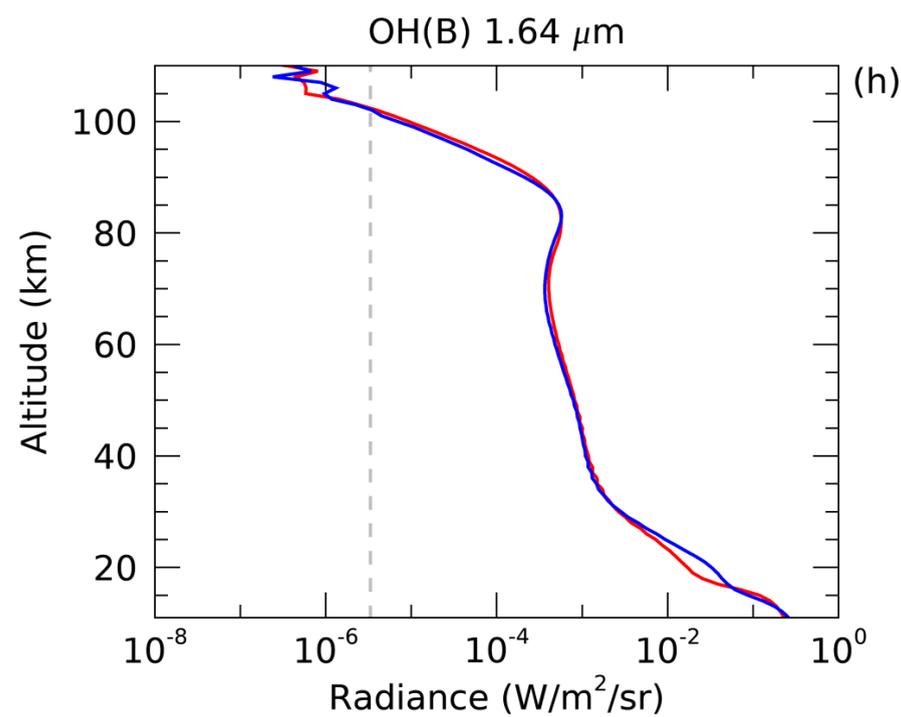
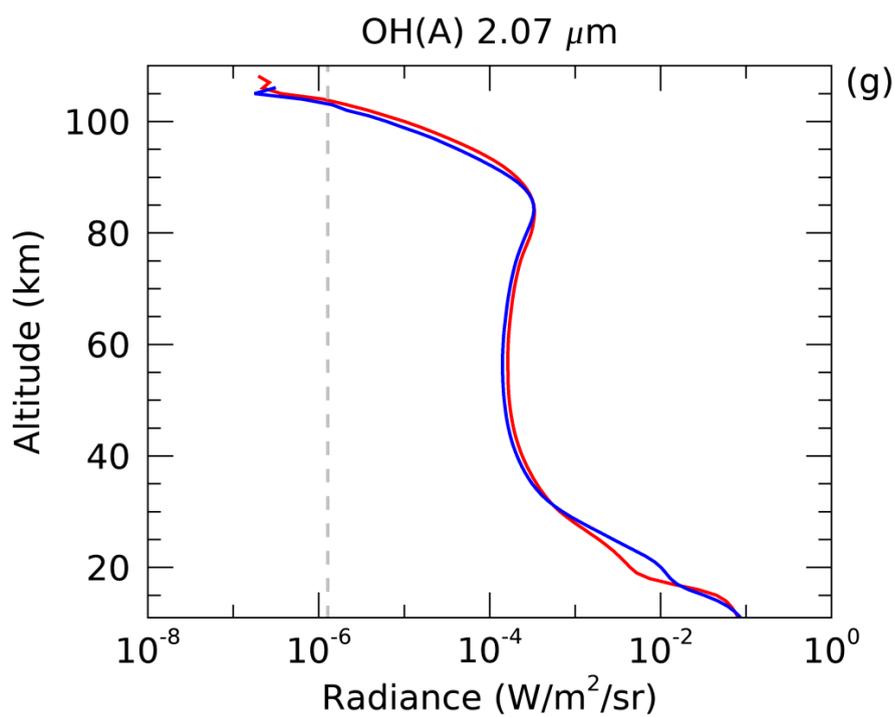
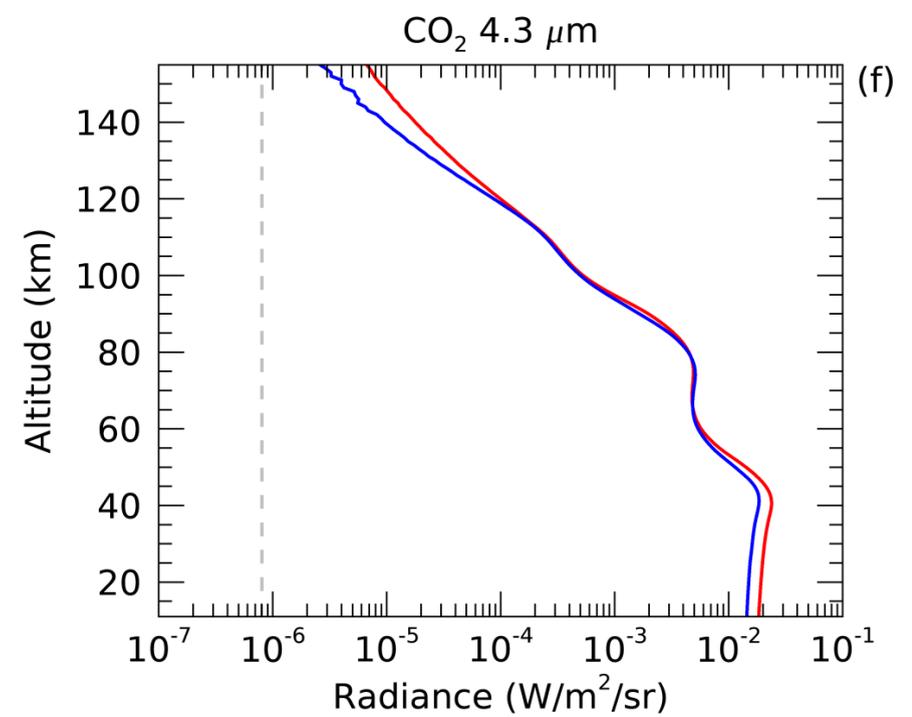
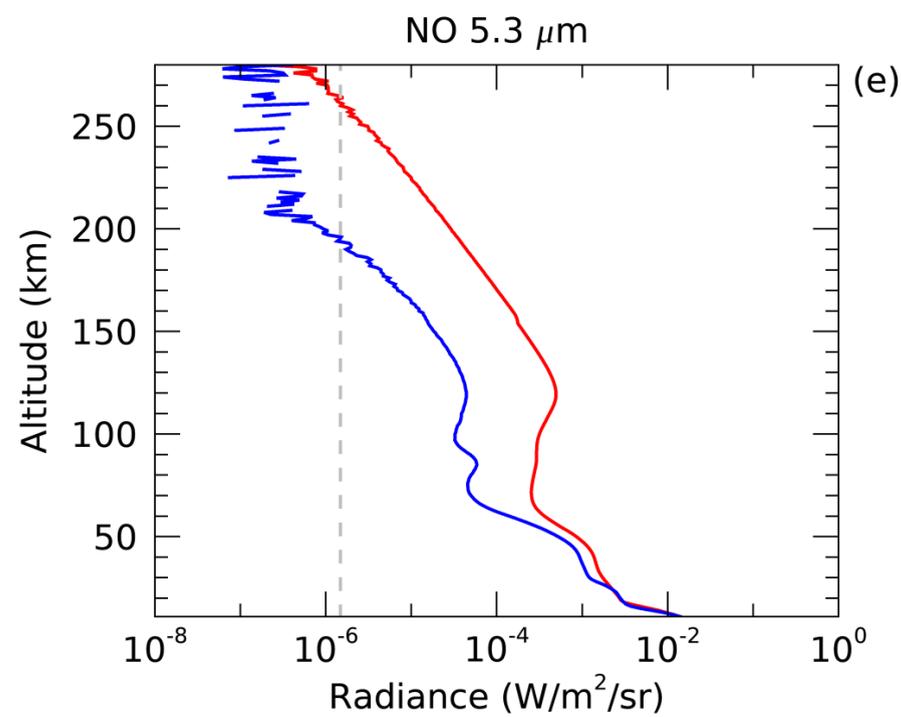
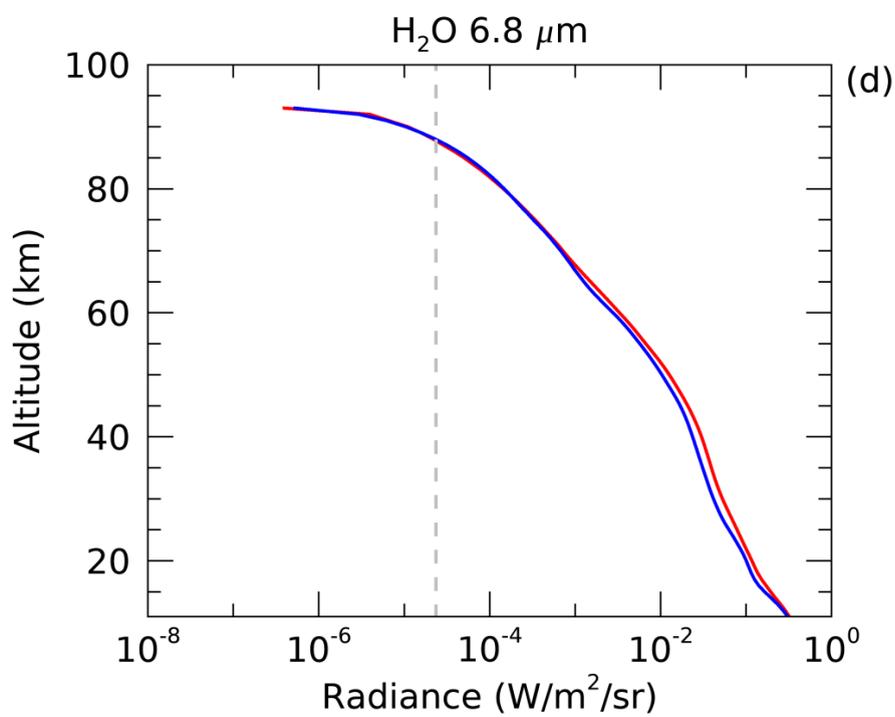
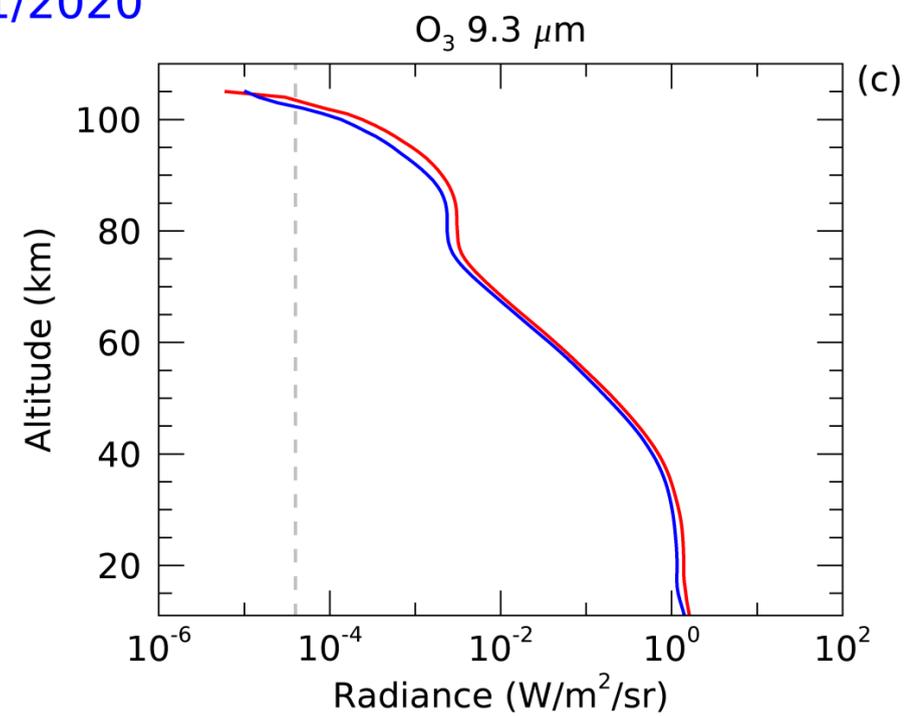
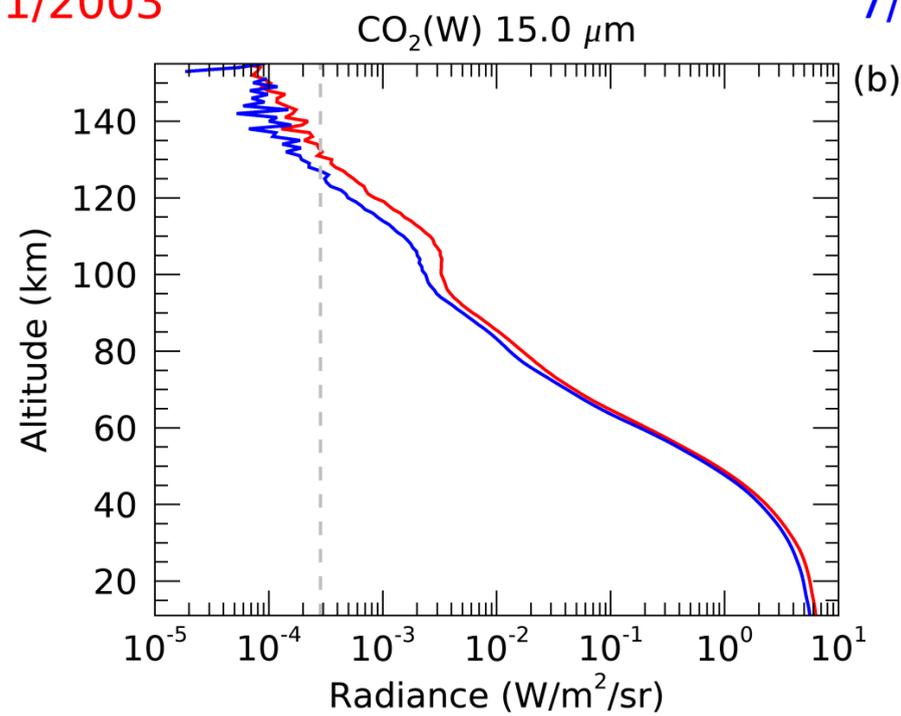
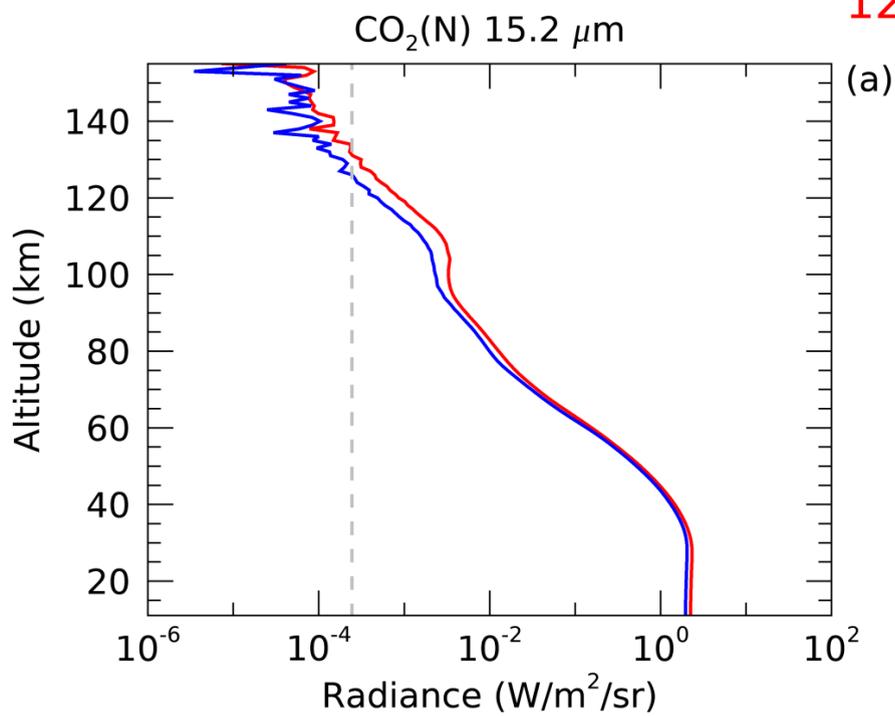


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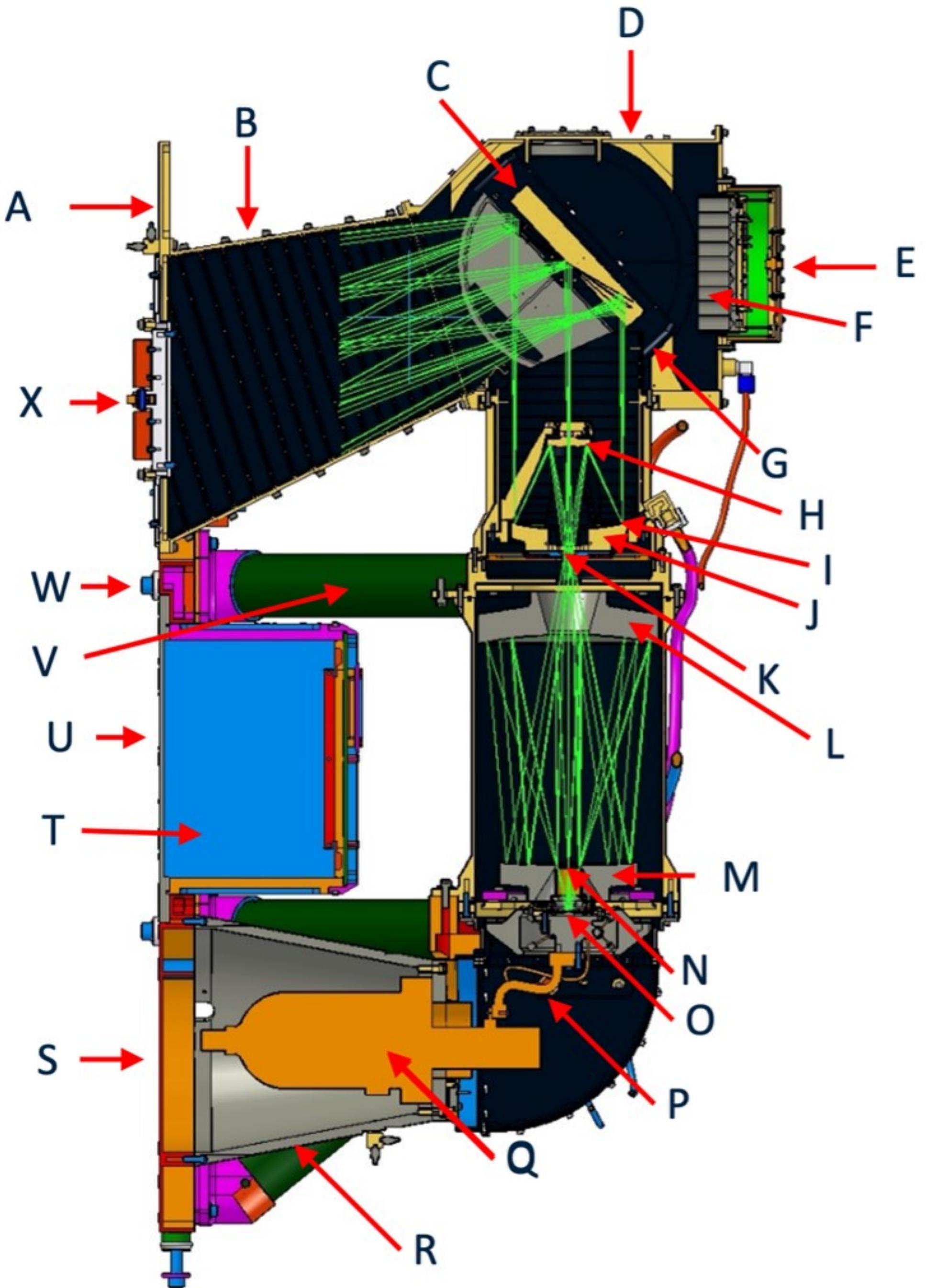


Figure 3.



Figure 4.

TME  
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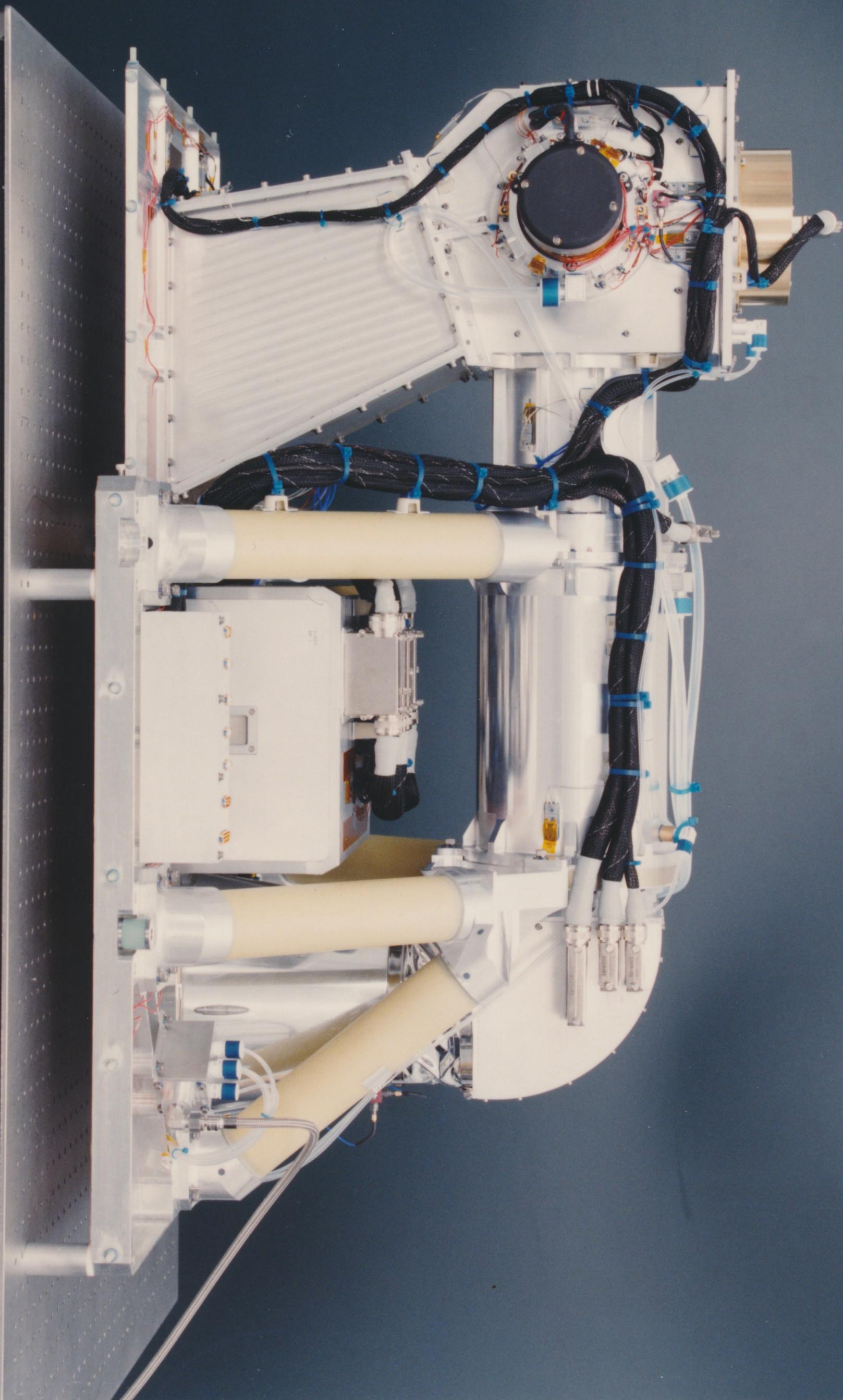


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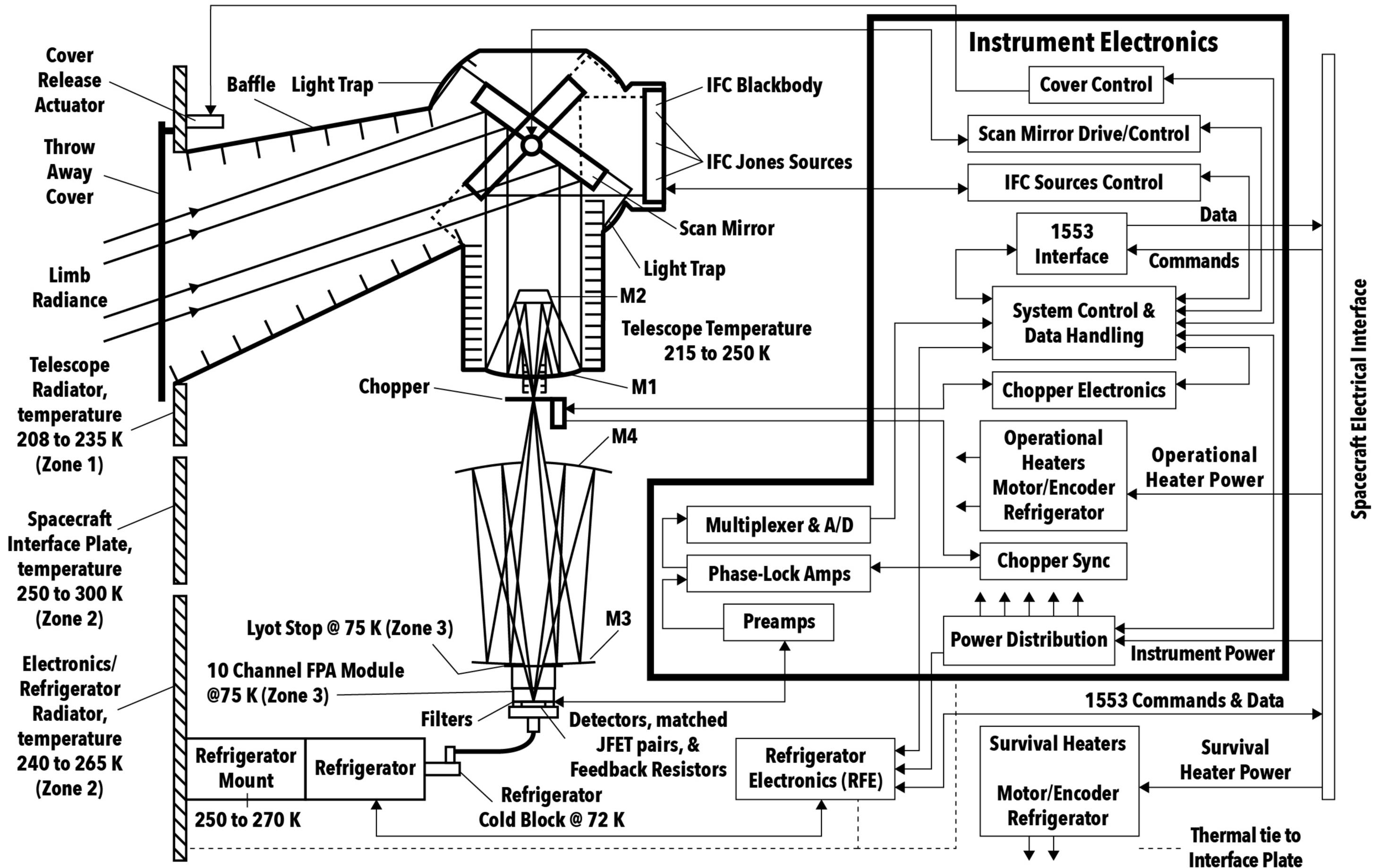
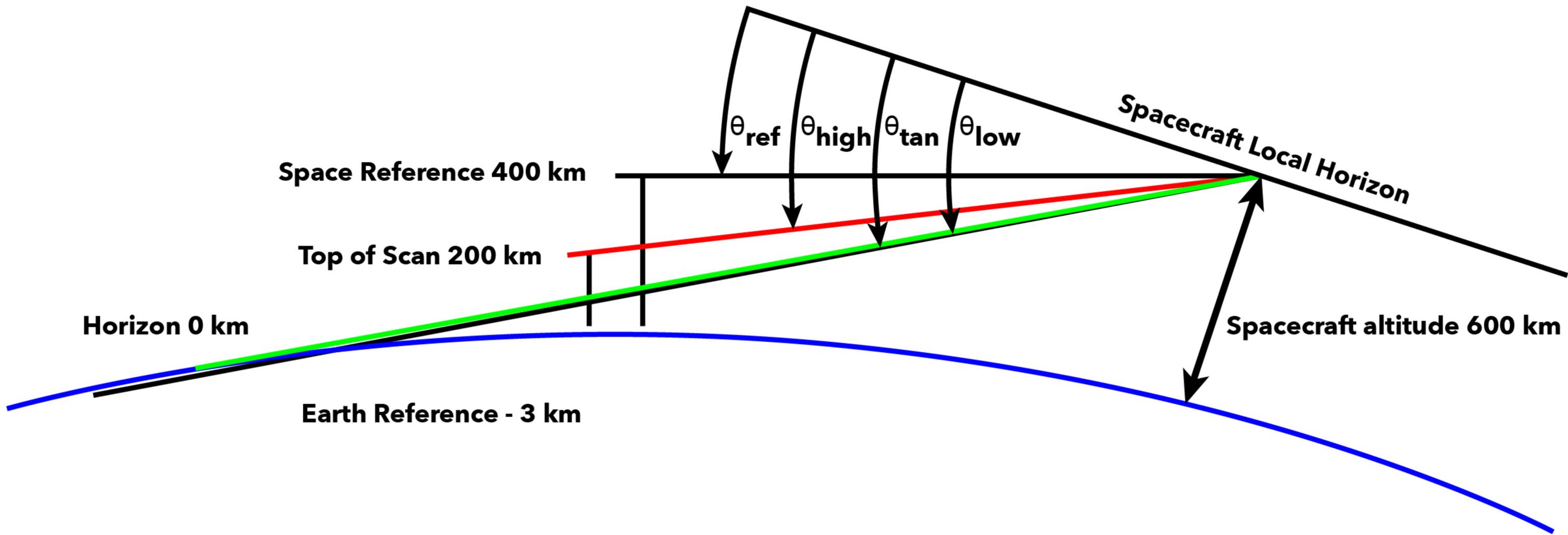


Figure 6.



Horizon 0 km

Space Reference 400 km

Top of Scan 200 km

Earth Reference - 3 km

Spacecraft altitude 600 km

Spacecraft Local Horizon

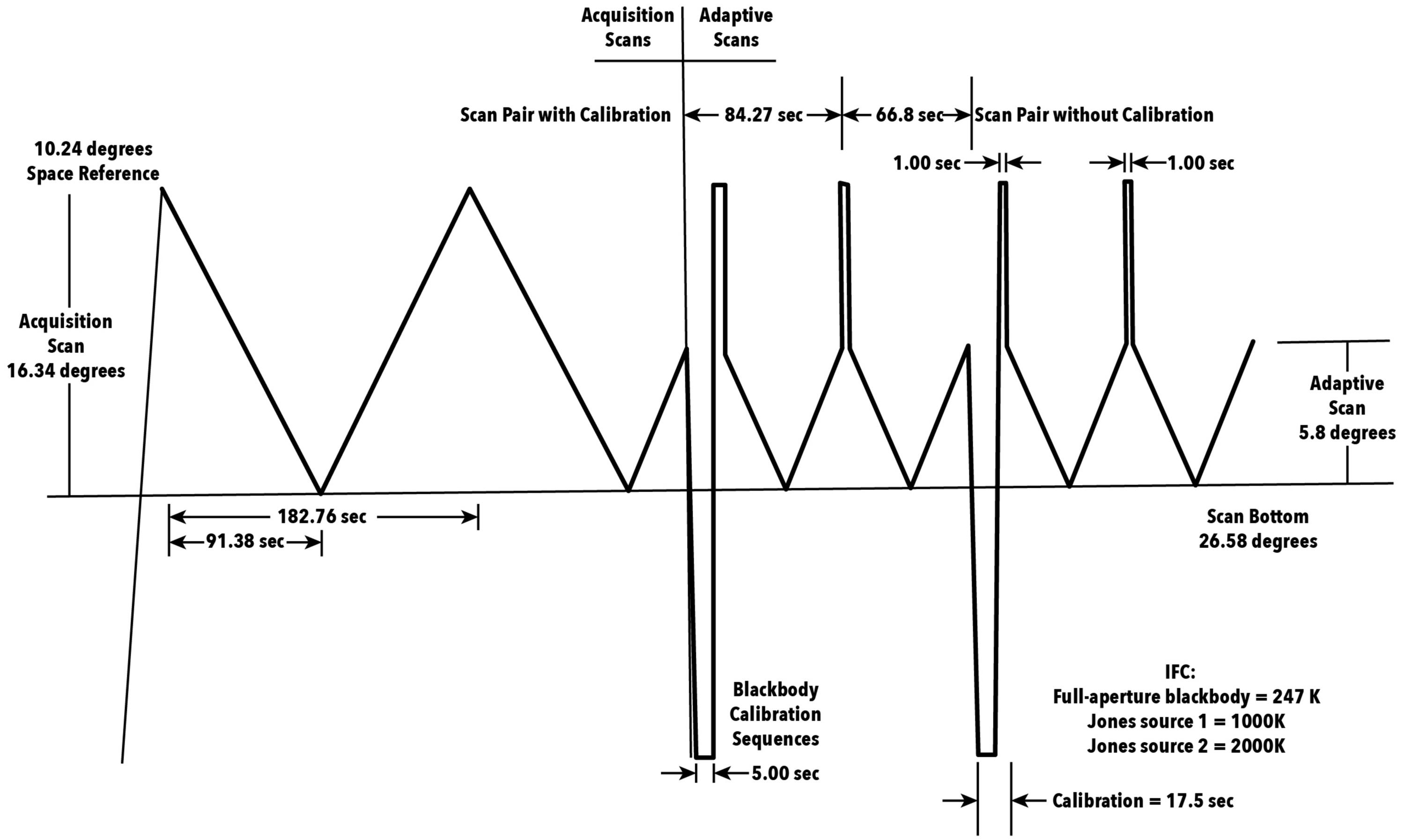
$\theta_{ref}$

$\theta_{high}$

$\theta_{tan}$

$\theta_{low}$

Figure 7.



**Not to Scale**

Figure 8.

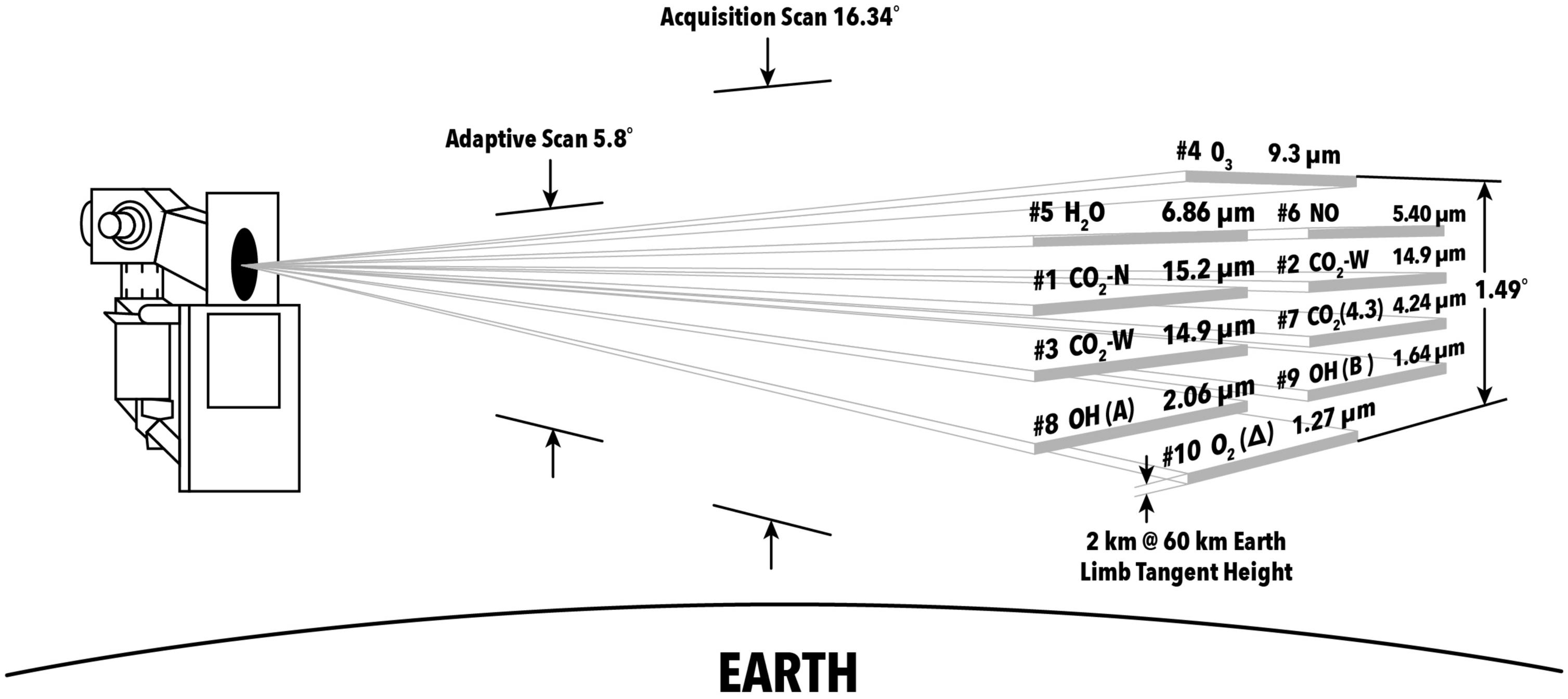


Figure 9.

Witness Mirrors

Scan  
Motor and  
Bearing  
Housing

IFC  
Blackbody

Chopper  
Location

Purge Inlet  
Connection and  
Filtered Manifold

Launch  
Depressurization  
Relief Valve

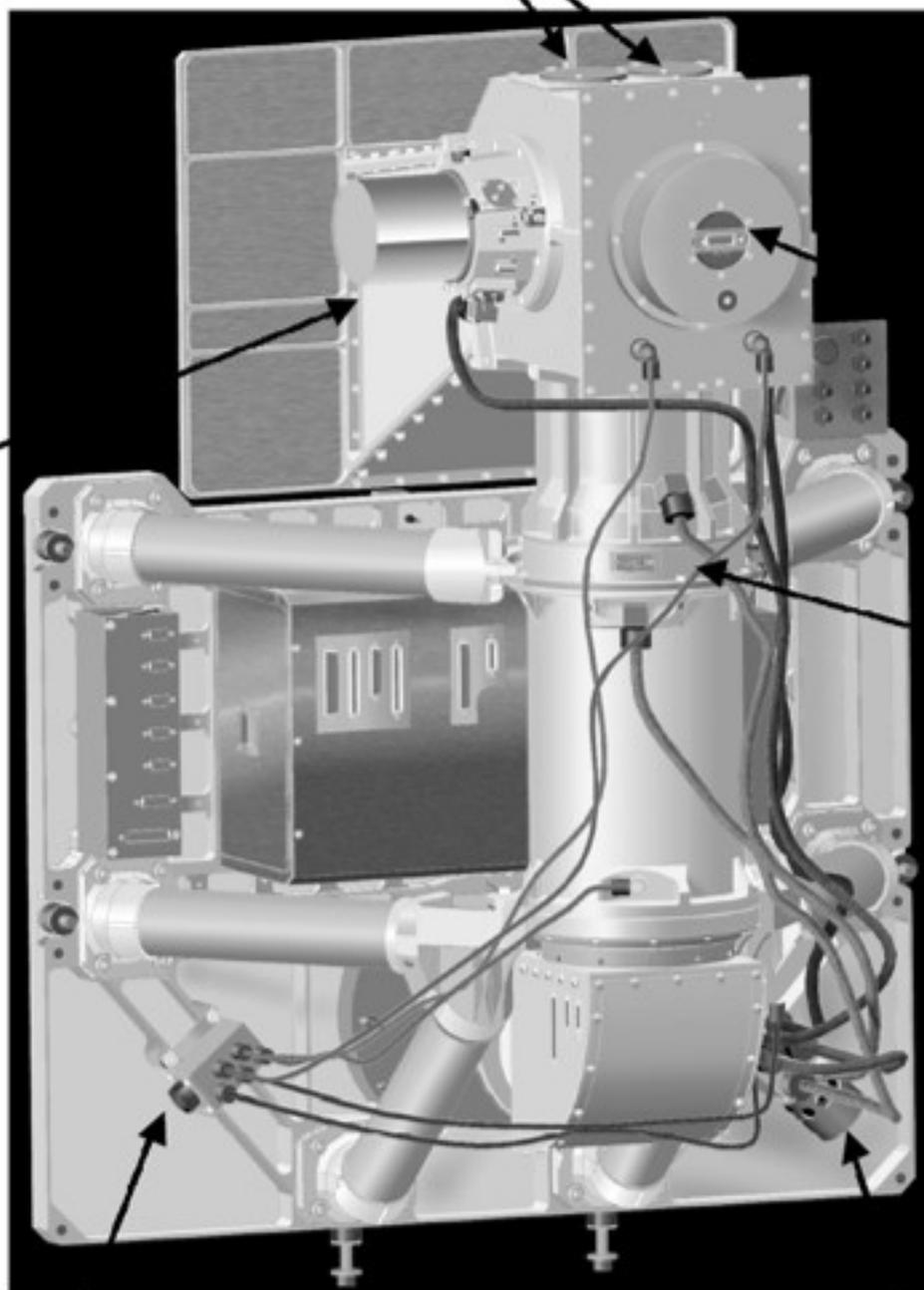


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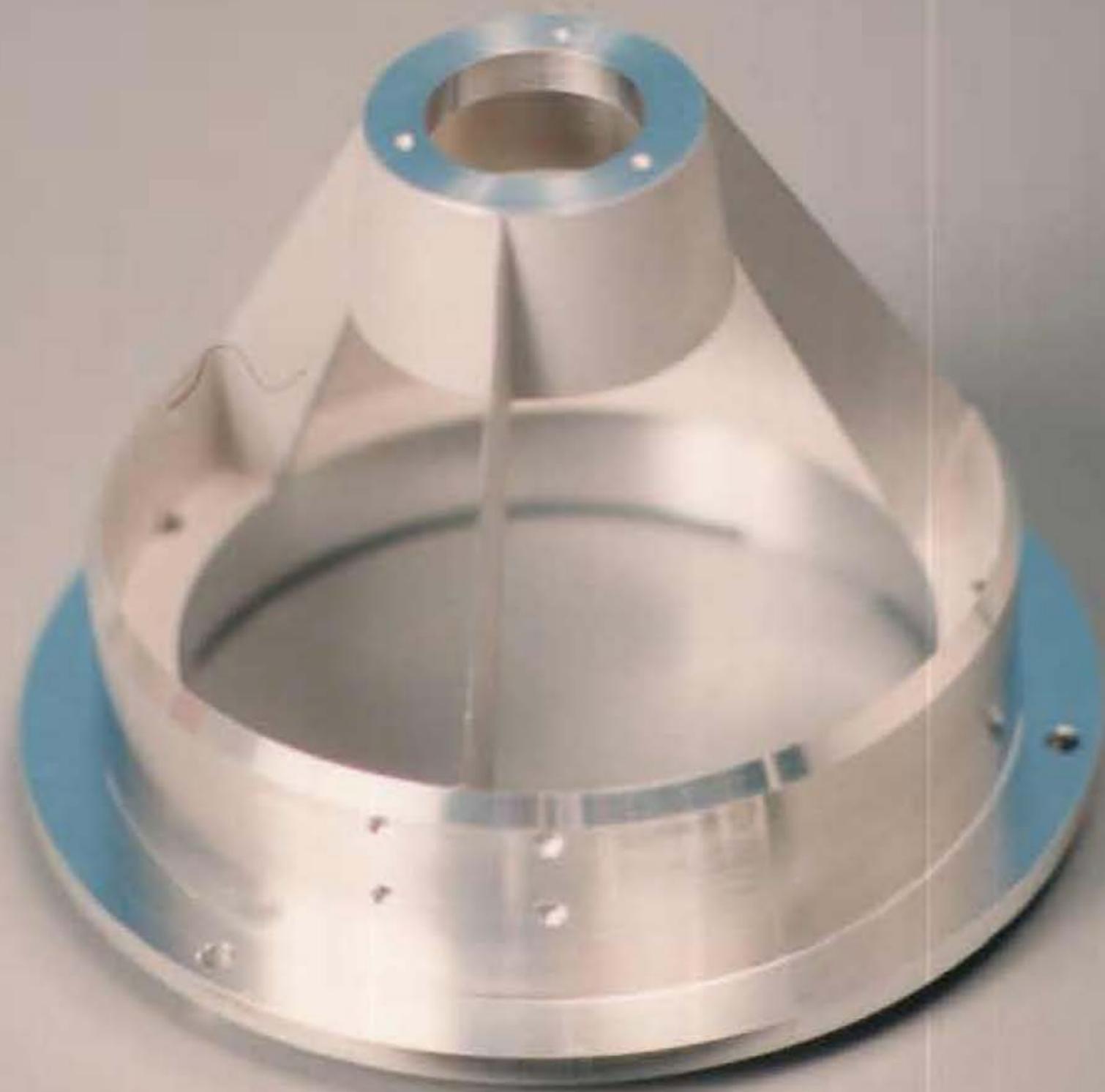


Figure 11.

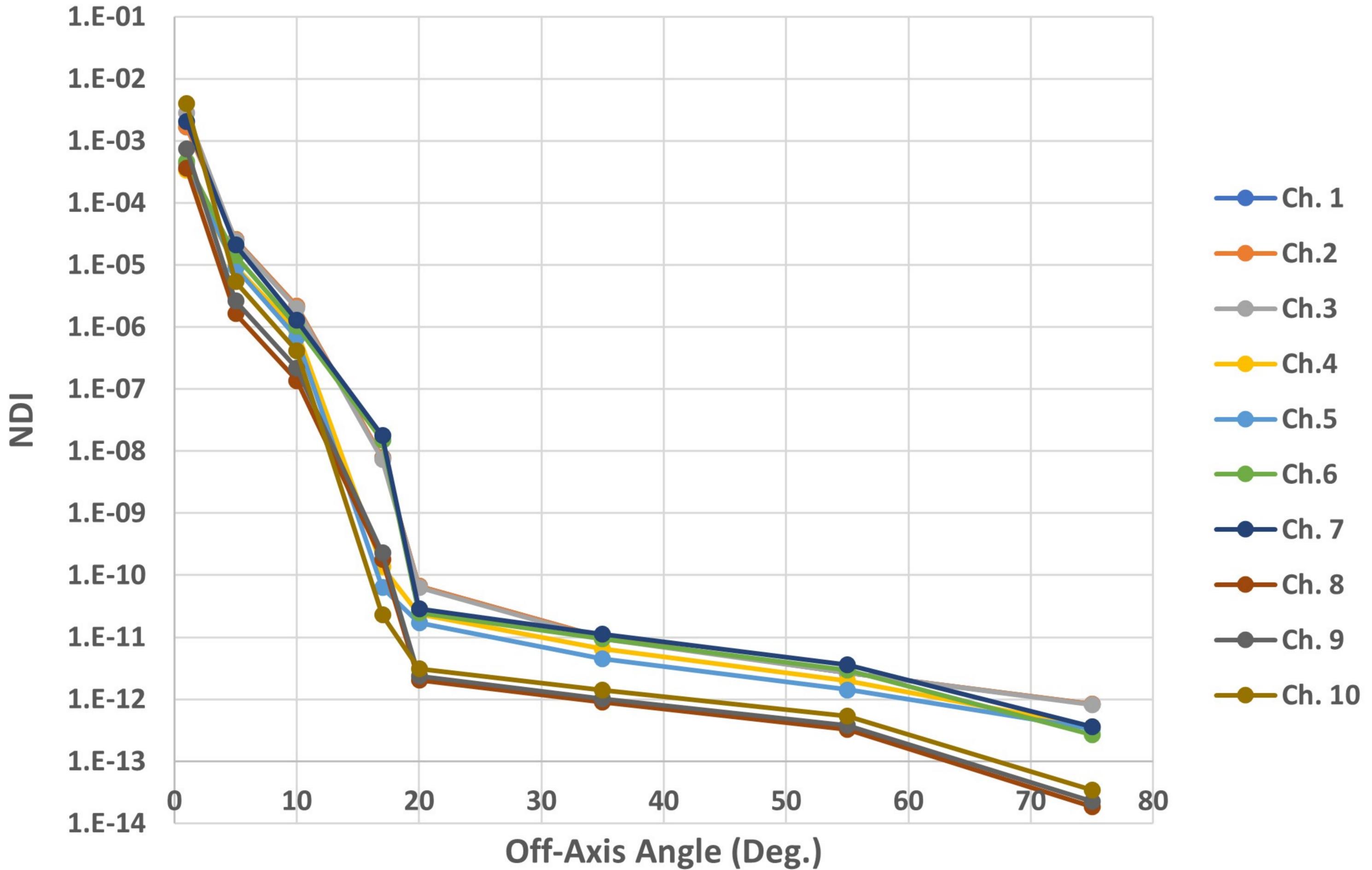


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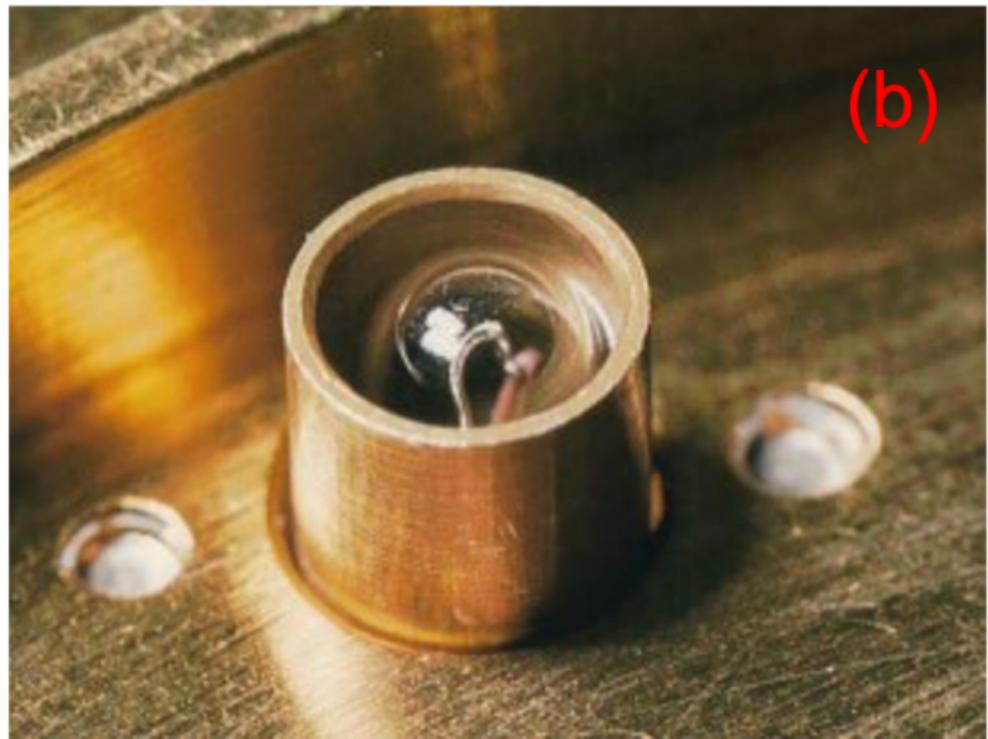


Figure 13.

Wax  
Actuator  
Pin  
Puller



Cover  
Witness  
Mirrors

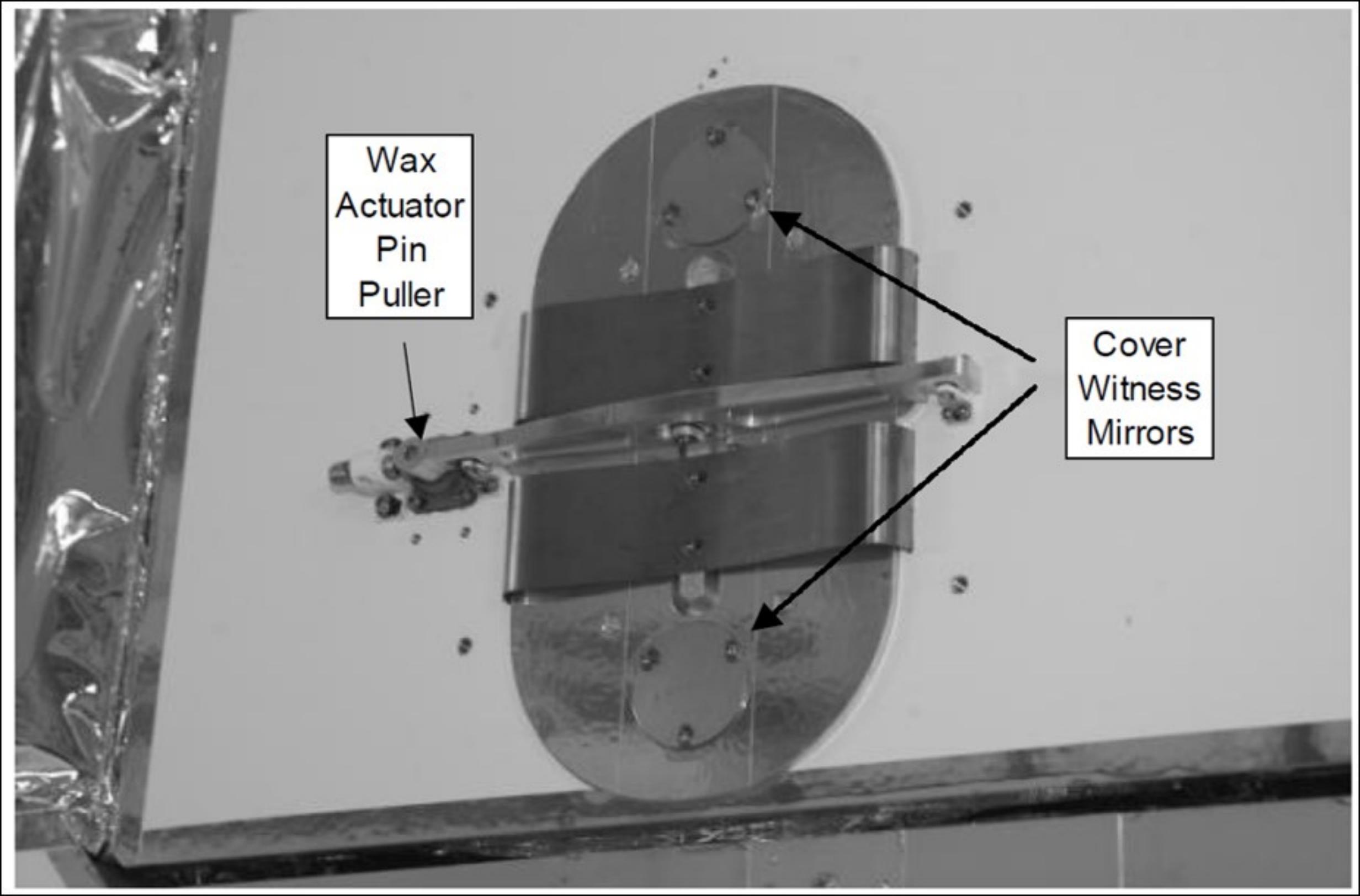
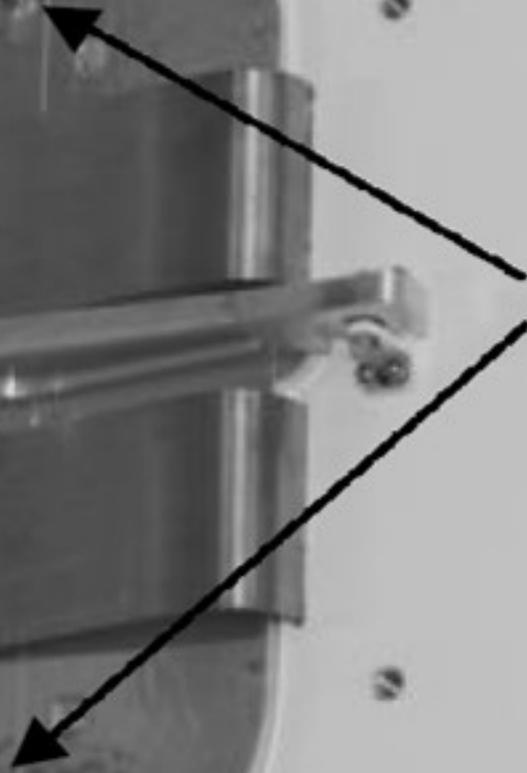


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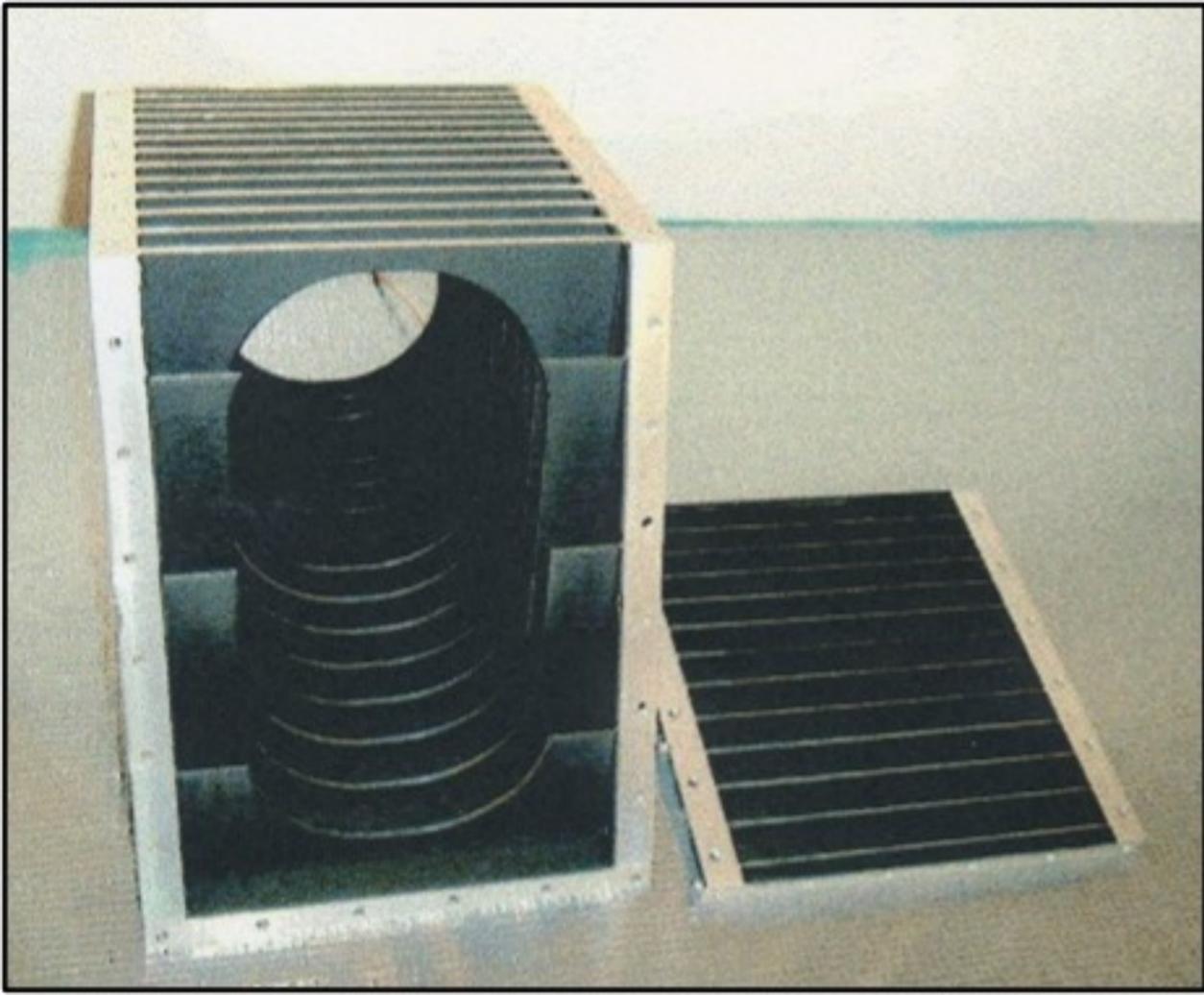
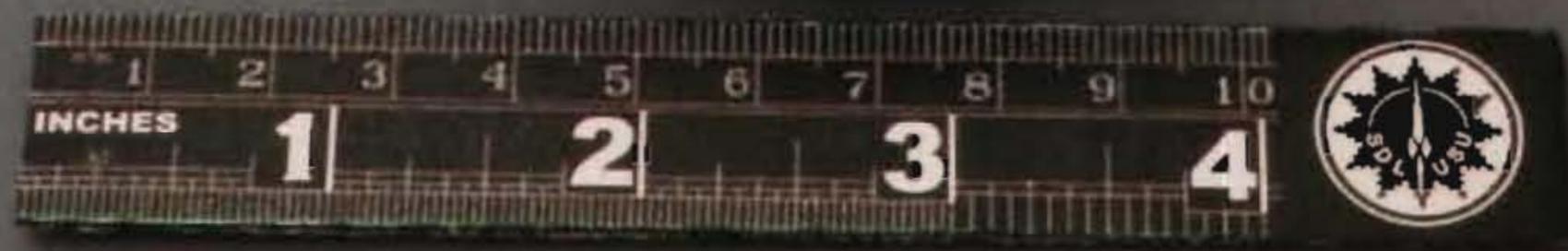
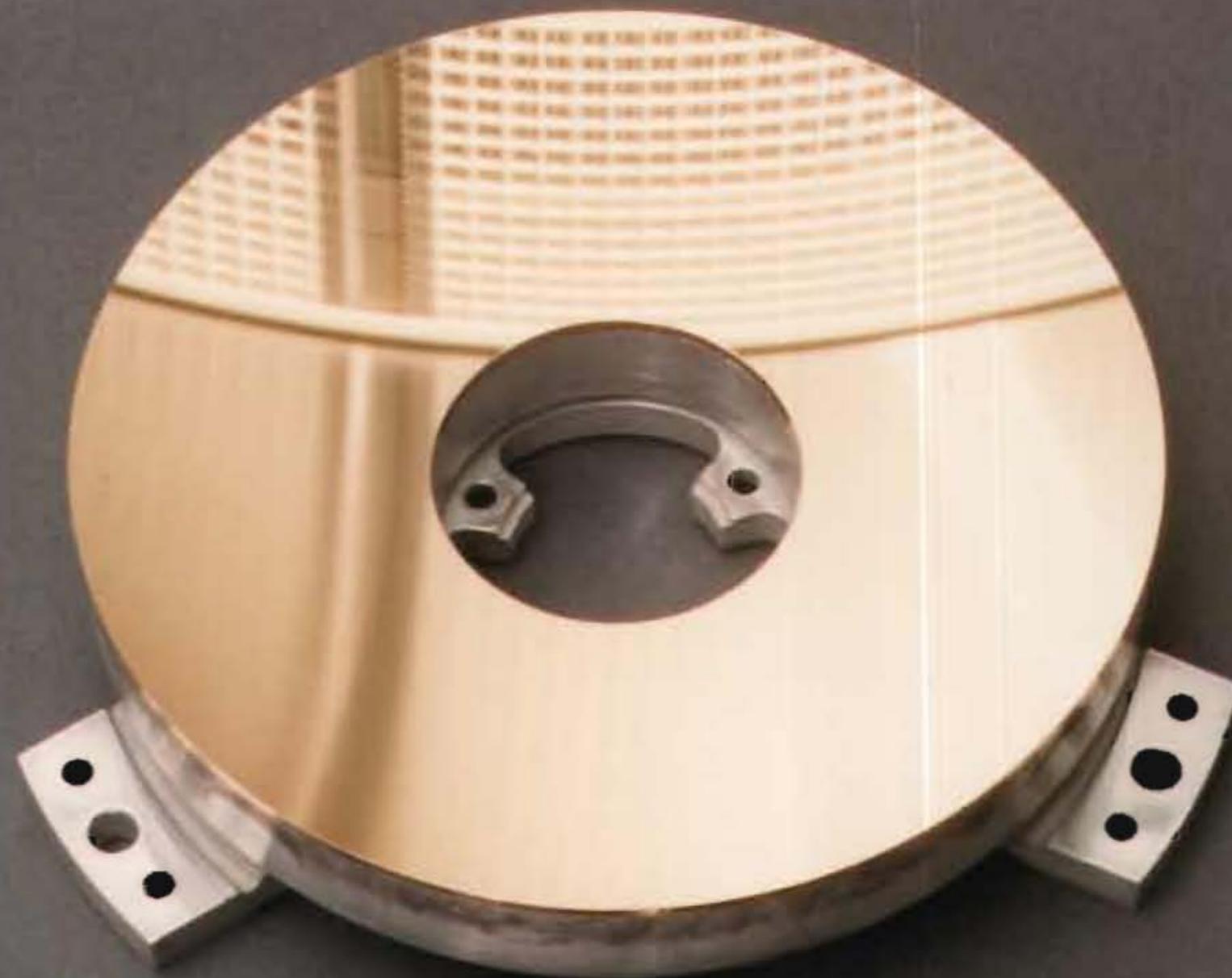


Figure 15.



Figure 16.



 **SABER M1**

Figure 17.

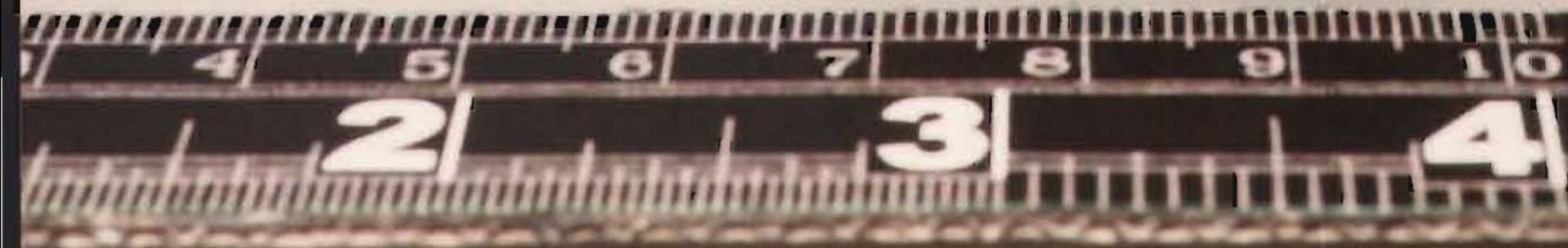


Figure 18.

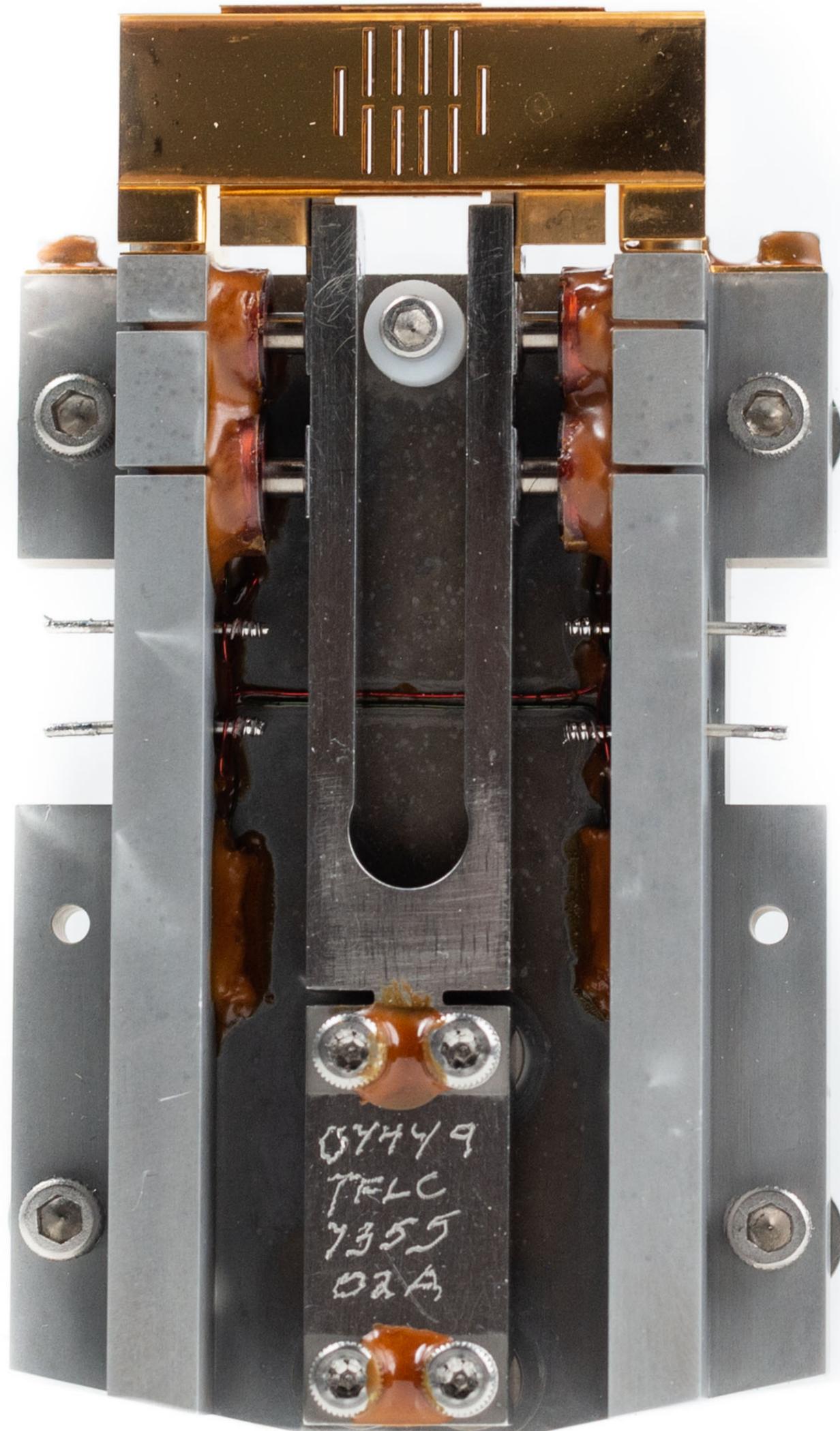


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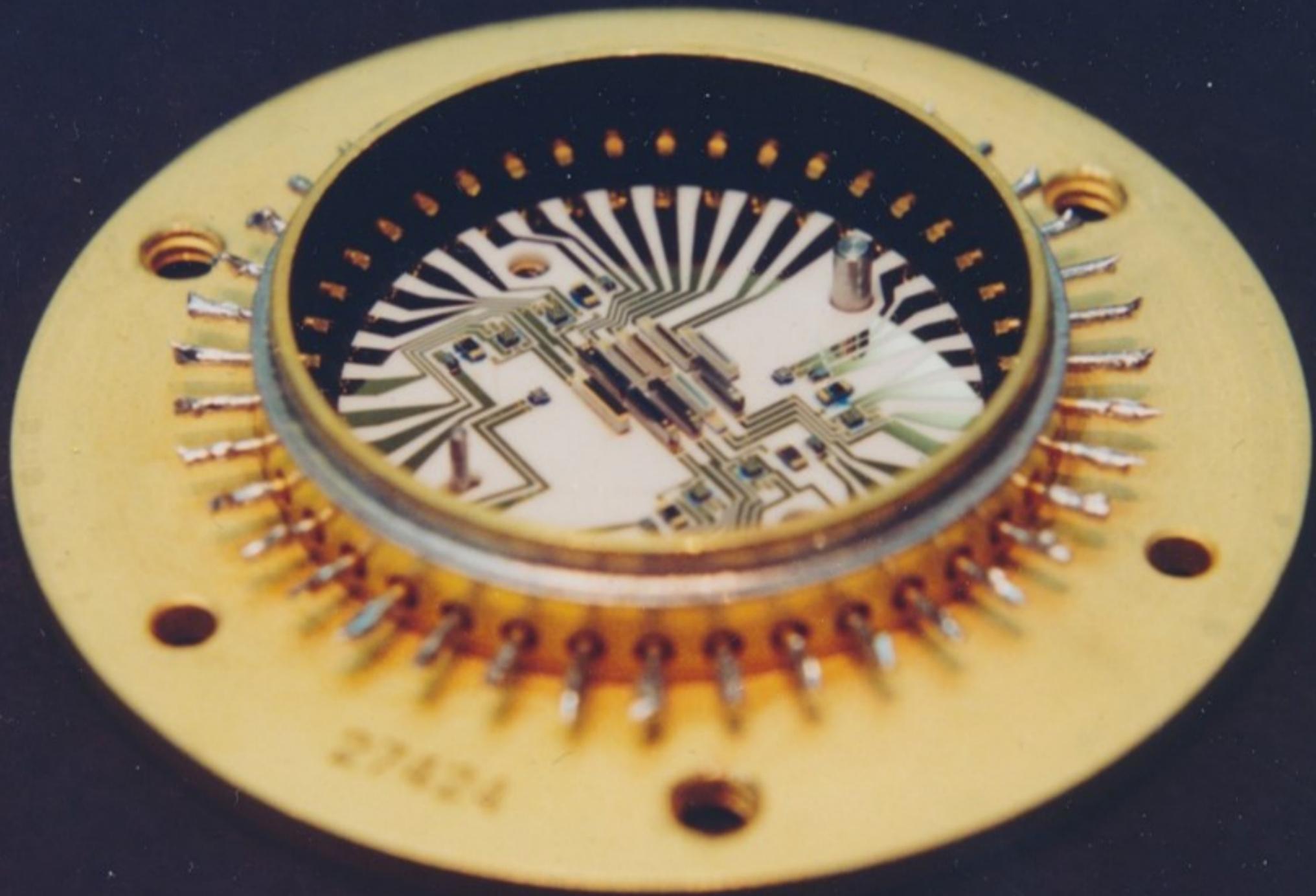


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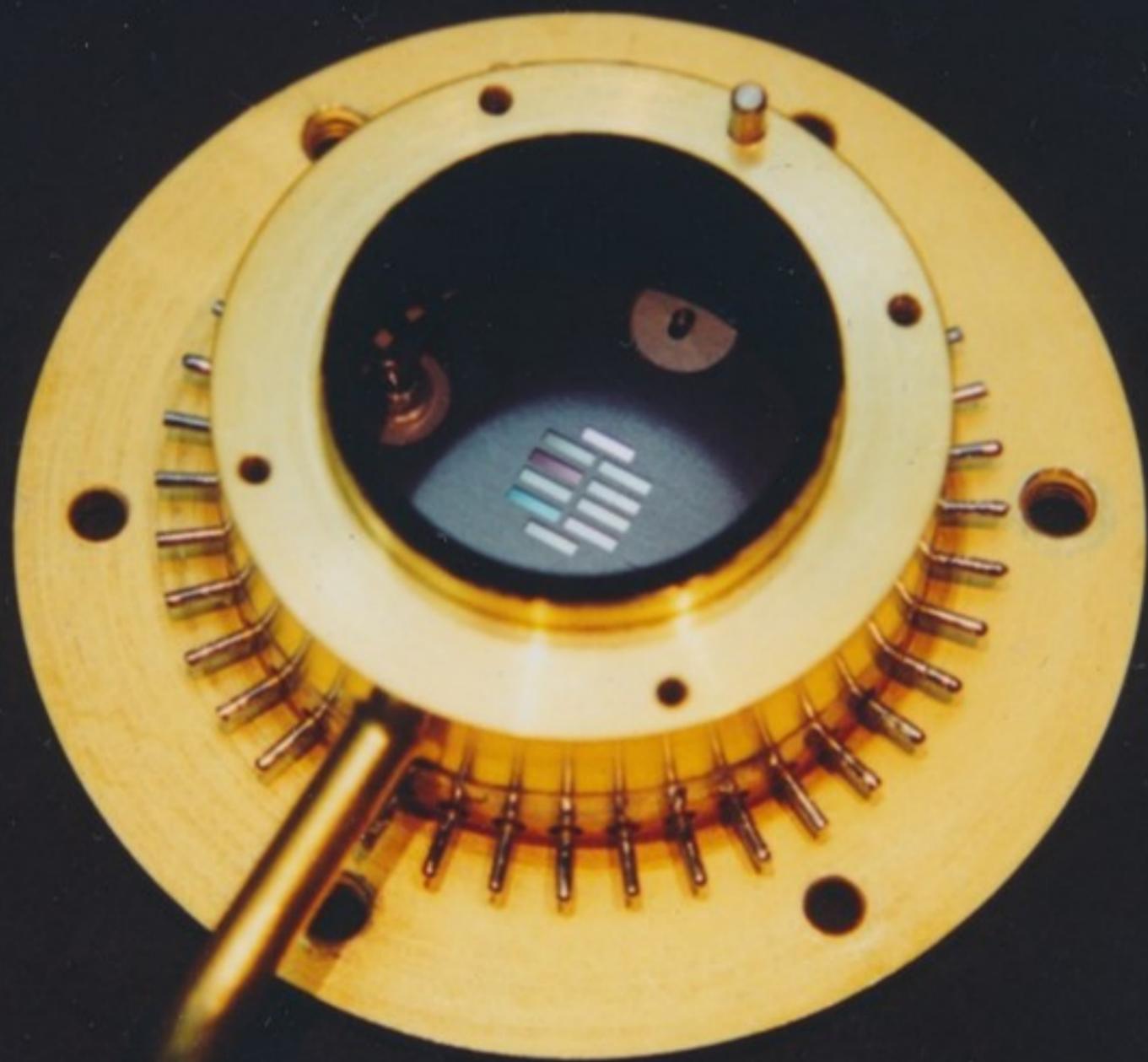


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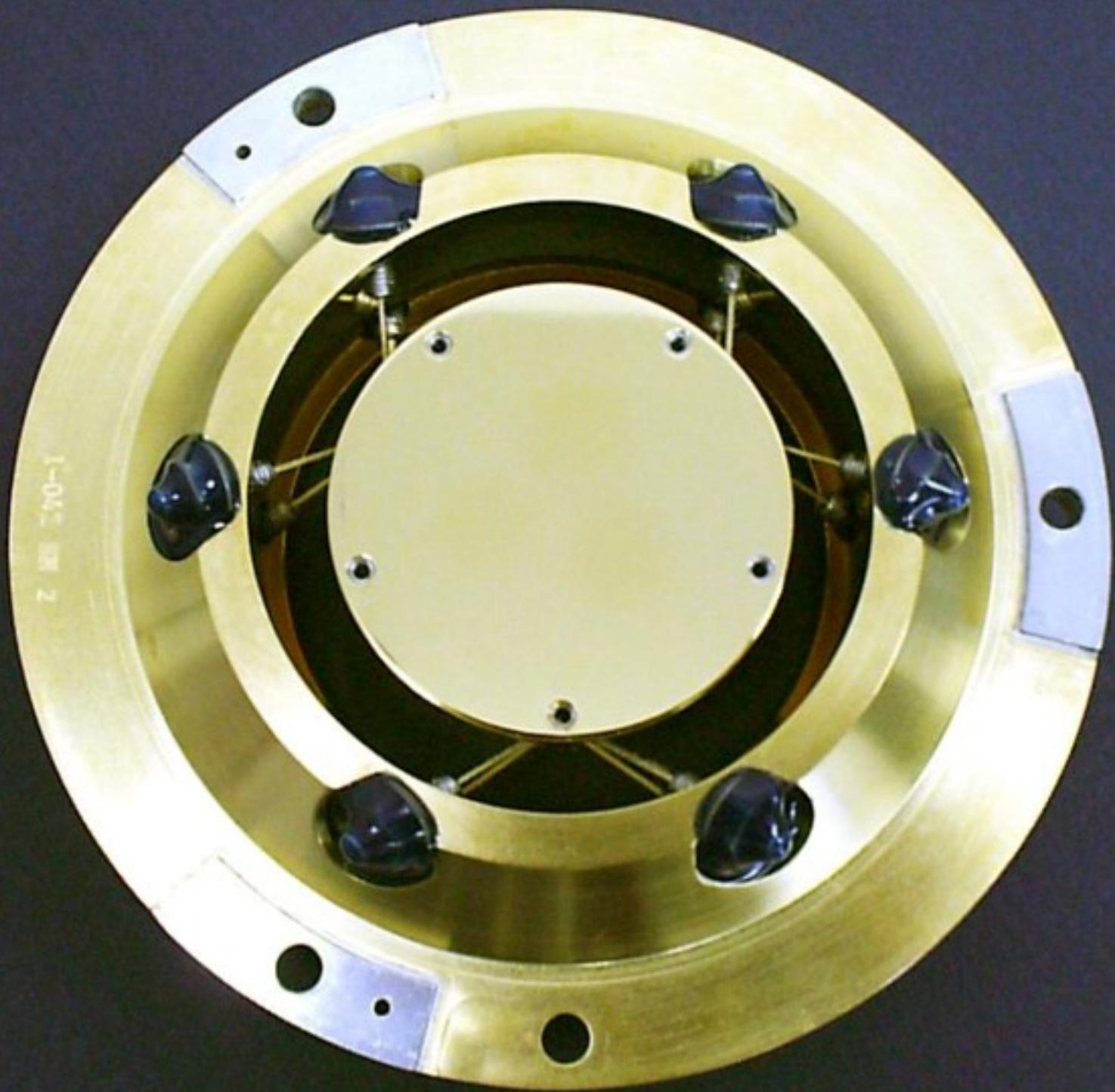


Figure 22.

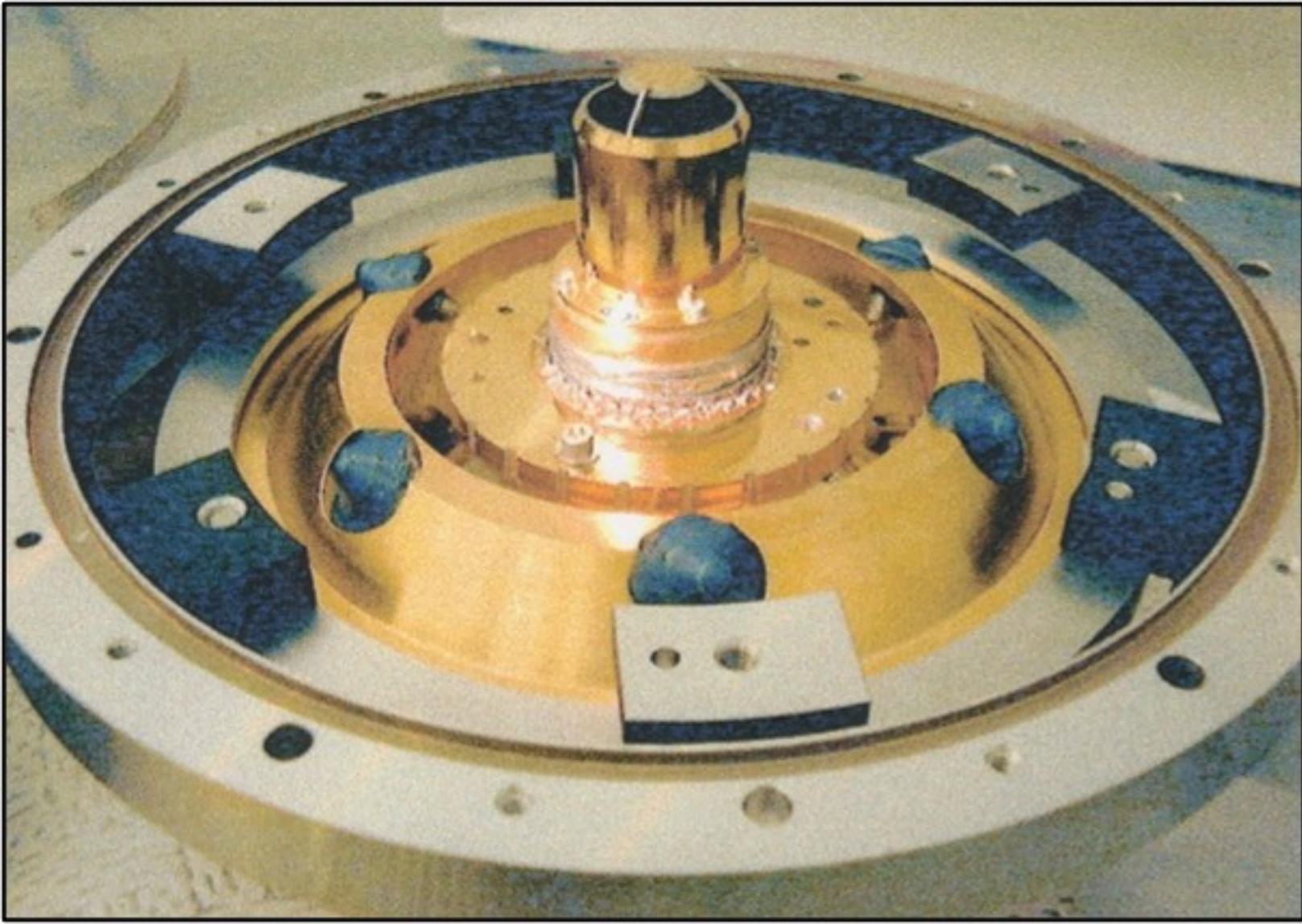


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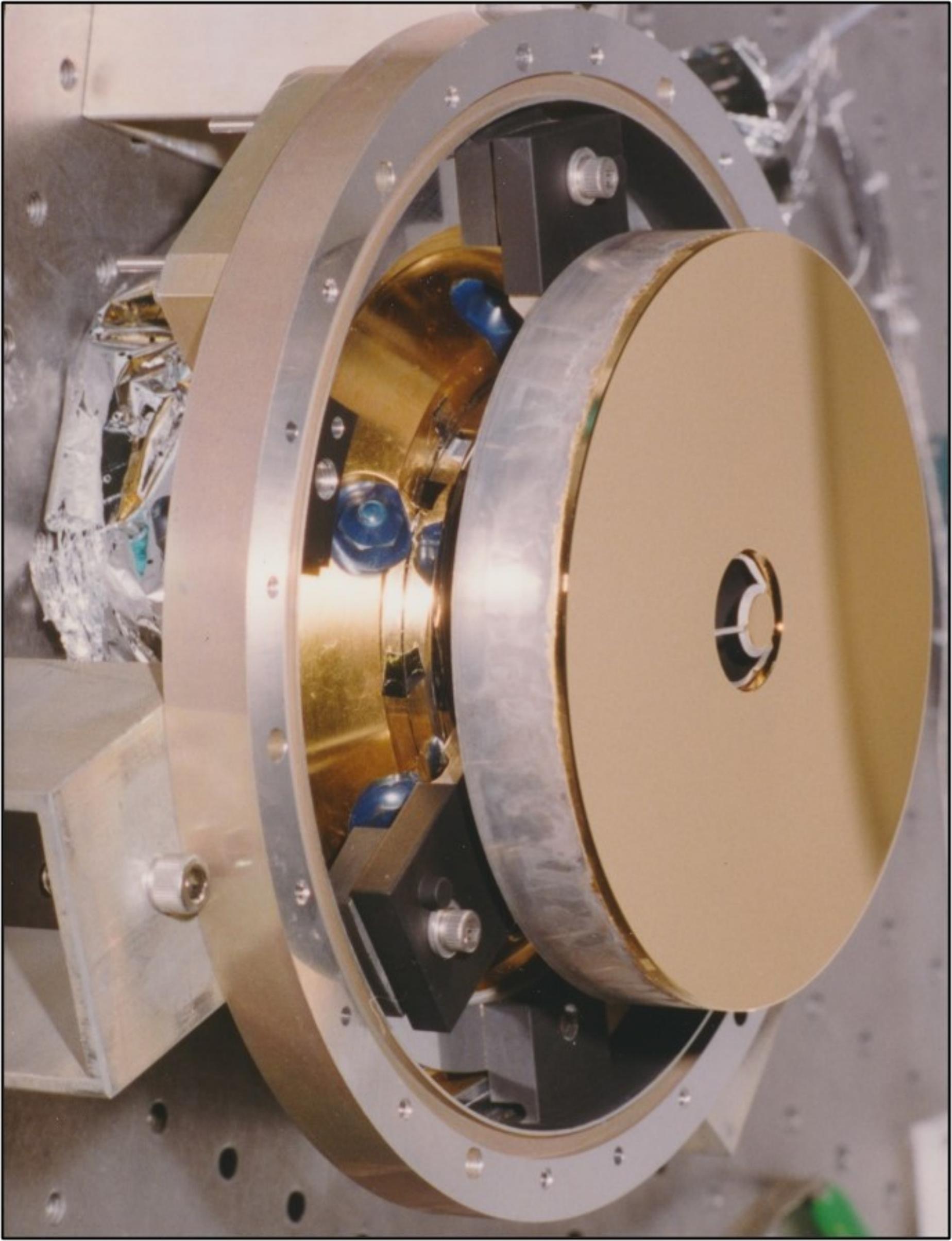


Figure 24.

