Design and test of cryogenic flex cables for the euclid near infrared spectrophotometer

W A Holmes\textsuperscript{1,4}, E Boehmer\textsuperscript{2}, C Bertagne\textsuperscript{1}, S Cheung\textsuperscript{3}, B Cho\textsuperscript{3}, H Cho\textsuperscript{1}, G Delo\textsuperscript{3}, R P Dillon\textsuperscript{1}, M Farris\textsuperscript{2}, A Feizi\textsuperscript{3}, N Ferraro\textsuperscript{1}, L Fischer\textsuperscript{2}, R Foltz\textsuperscript{2}, K Hong\textsuperscript{2}, M Jhabvala\textsuperscript{3}, E Kan\textsuperscript{3}, R Kopp\textsuperscript{2}, J Maiten\textsuperscript{2}, D Markley\textsuperscript{1}, A R Morgan\textsuperscript{1}, M Nguyen\textsuperscript{1}, S Pravdo\textsuperscript{1}, C Ruiz\textsuperscript{1}, M Runyan\textsuperscript{1}, A Skalare\textsuperscript{1}, A Waczynski\textsuperscript{3}, Y Walters\textsuperscript{3}, A Wong\textsuperscript{1} and F Zhong\textsuperscript{1}

\textsuperscript{1}Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
\textsuperscript{2}Teledyne Imaging Sensors, Camarillo, CA
\textsuperscript{3}Detector Characterization Laboratory, Goddard Space Flight Center, Greenbelt MD
\textsuperscript{4}Correspondence should be sent to warren.a.holmes@jpl.nasa.gov

Abstract. We describe the design and testing of the Cryogenic Flex Cable (CFC) delivered for the Near-Infrared Spectro-Photometer (NISP) instrument \cite{1} for the ESA Euclid mission \cite{2, 3}. The Euclid spacecraft is scheduled for launch in the summer of 2022. It will observe $\sim 1/3$ of the total sky using a telescope with 1.2m SiC primary mirror, passively cooled to $\sim 125\text{K}$, and containing Visible Imager (VIS) \cite{4} and NISP focal plane instruments, from an orbit at the Earth-Sun L2 lagrange point. At the heart of the NISP instrument is a 4X4 mosaic focal plane of Teledyne H2RG infrared detector arrays held at 100K. The CFC described here are designed to link each detector array to a dedicated packaged cryogenic electronics assembly held at $\sim 137\text{K}$ with minimal heat leak to the 100K stage and to withstand handling and launch vibrations. Prototype CFCs were developed and tested by Teledyne. The final 7-layer CFC flexible printed circuit boards and Airborn nanoconnectors were provided by Teledyne and assembled for flight at the Jet Propulsion Lab (JPL). Flight qualification CFC were made and subjected to thermal conductance, thermal emissivity, thermal cycle, survivability to bend, vibration and normal mode testing at JPL. The flight CFC were subject to bake out and thermal cycle at JPL and then tested with the flight detectors and electronics at Goddard Space Flight Centers Detector Characterization Lab. The results of the qualification tests as well as the measured characteristics of the 41 manufactured CFC are summarized.

1. Introduction
The Cryogenic Flex Cable (CFC), described here and shown in figure 1, electrically connects the Teledyne H2RG infrared detector arrays \cite{5, 6, 7} or Sensor Chip Assembly (SCA) to the cryogenic Sensor Chip Electronics (SCE) package that includes the Teledyne SIDECAR ASIC \cite{5}. Together, these three components are called a Sensor Chip System (SCS). A mosaic of 16 SCS are mounted in focal plane of the Near-Infrared Spectro-Photometer (NISP) instrument \cite{1, 8} for the European Space Agency (ESA) Euclid mission \cite{2}. Signal lines in the CFC include analog supply, digital supply, command and clocking signals from the SCE to the SCA and signal voltages from the SCA to the SCE. Key design requirements are summarized in table
Figure 1. Representative image of a completed CFC ready for test.

1. Additionally, the CFC had to be mechanically robust to typical handling conditions and to vibration from rocket launch.

| Table 1. Key CFC design requirements. |
|---------------------------------------|
| Average Value | Measurement Error/Range | Requirement Value |
| Wire Count (N) 66 | NA | 60 < N ≤ 87 |
| Mass (g) 11.1 | 0.17 | < 20 |
| Length (mm) 107.1 | 0.12 | 107 ± 0.3 |
| Thermal Conductance (mW/K) 0.846 | 0.014 | < 1.5 |
| Thermal Emissivity 0.0505 | +0.037, −0.00 | < 0.1 |
| Molecular Contaminant (µg/cm²) 0.04 | +0.06, −0.02 | < 0.5 |
| Particle Contaminant (µm) 200 | +100, −50 | < 250 |

The low thermal conductance at fixed cable length drove the design to a flex print architecture with copper wiring and a constantan ground plane. The remainder of the design was guided by general electrical design principles. Analog signal, analog supply and digital lines were separated into three distinct regions on the cable. Ground return lines were placed nearby corresponding supply lines. Supply and ground return wires were specified for lower resistance than signal wires. The SCE provided star ground for each SCS where digital and analog grounds were connected. The constantan ground plane was placed within layered metal polyimide laminate beneath the analog supplies and video signals and terminated on the SCE side of the CFC. No voltages higher than 5V are possible using the drive electronics, so polyimide is sufficient as an insulator. A thin gold layer is evaporated on the top and bottom of the flex print for low thermal emissivity. Although the function of this gold layer is thermal, it is electrically connected to chassis ground to avoid space charging. This electrical connection of evaporated gold layer is made using dimple features on the flex cable that connect it to the analog ground wire in the flex. The connector backshell is pressed on to the flex print over gold metal pads which is sufficient grounding to avoid electrostatic discharge during handling. Solid, milliohm, chassis ground connection to the backshell is made once connected to the SCE.
2. Cable Manufacture
The CFC flexible printed circuit boards (flex print) is an IPC-2223 type 3 design manufactured to IPC-6013C class 3 standard [9]. A short section of the CFC, starting at the 91 pin SCE connector, is a 7 layer semi-rigid section. The semi-rigid section transitions to a 3 layer flex print for the majority of the length and terminates in the 85 pin SCA connector. Routing for cross connections required at the SCE connector is through copper layers 1, 2, 6, and 7. The core, layer 4, is a constantan conductive plane and next most inner layers 3 and 5 are copper power and signal lines. Flex prints were manufactured in panel form with 5 flex prints to a panel. Gold with a Ti adhesion layer was evaporated on both sides of the flex prints. Reflectivity measurements at optical wavelengths of the gold coating were made as a prescreening test of the quality of the outer gold coating. The thermal emissivity requirement is verified in a second test on a qualification cable, as described below. Complete electrical continuity, isolation resistance, gold overcoat resistance are measured to identify good CFC prior to removing the individual flex prints from the panel. Panels with A/B coupons that passed IPC-6013C class 3 inspection criteria were accepted for prototype and flight build. Additionally, two flex prints from the production lot were thermal-cycled 10 times from 77K to 323K. Visual inspection and electrical continuity testing were performed before and after the 10 thermal cycles as well as a destructive physical analysis cross-section and visual inspection after thermal cycling. The two flex prints passed this additional pre-screening testing and inspection.

Airborn nanoconnectors define the wiring interface between the SCE, CFC and SCA. The connector design used for Euclid was developed by Teledyne in cooperation with Airborn for high reliability. The connectors for Euclid were pre-screened at the manufacturer before delivery, including 100% pre-pot visual and 100% connectivity measurement. The requirement of 100 mate-demate cycles was verified by the manufacturer. Flight connectors and any GSE equipment mated to flight connectors were inspected before each mate operation. In normal use of the connector, the phenolic around a very few connector pins is scraped at each mate-demate creating strings of material. The strings of material are left in place since each is trapped under the socket at the next mate/demate. If the scraping generates a string of material comparable to the pin spacing or are loose, the string is picked off with a small plastic tool.

Fixturing was used to hold precise position of connectors and flex print during connector soldering. After soldering, all solder joints were visually inspected to J-STD-001FS [10]. The solder joints were then potted with cryogenic compatible epoxy. Preforms were used to control the volume potting epoxy and prevent flow during cure. Following cure of the potting material, the potting preforms were removed and a bead of epoxy added to the transitions between the rigid and flex and cured for strain relief. The CFC was removed from the manufacturing tooling, weighed and installed flat in a CFC handling fixture for transport to bake out. A few cables (6 of 41) were found to have small tears or nicks at the edges after manufacture. These cables were rejected for flight due to possible propagation of the tear during vibration. Otherwise, these nicked cables were fully functional and used for various screen testing of SCAs and SCEs.

After assembly, each CFC was baked out at 95°C to minimize outgassing. To determine bake out time, two pathfinder CFCs, were baked in a chamber equipped with a Quartz Crystal Monitor (QCM) collector at −20°C. The QCM stabilized after a 72 hour bake which defined the bakeout time for subsequent CFCs. Post bake, the non volatible residue (NVR) for each CFC was measured. Typically, the NVR was in range of 0.01 – 0.05µg/cm². The maximum measured on any of the CFCs was 0.1µg/cm² still a factor 5 below requirement of 0.5µg/cm².

The CFC has shape memory. So the CFC is pre-formed in a custom cable bending fixture prior to electrical and cryogenic testing. The pre-forming procedure is designed to mimic the actual handling of the CFC during installation into the flight NISP instrument. In this way, all bends of the CFC are over the same range and direction. This controlled procedure was designed to improve the repeatability of the shape of the CFC in order that it does not contact NISP.
structure during vibration. In the NISP instrument there are two possible bend configurations called the tight S and loose S as shown in figure 2. Prebend into the tight S configuration was chosen since it puts the most stress on the CFC, especially at transitions to the connector attach locations. Therefore the tight S during thermal cycling is a worst-case stress environment. Once pre-formed, the CFC was tested and then stored in bent configuration in a specially designed storage fixture, figure 2.

3. Cable Testing
All CFC, including pathfinder, flight model and qualification model were subjected to thermal cycling as a screening test. All electrical traces were monitored during the thermal cycling. The signal, power and ground wire resistances ranged from 0.04 to 0.12Ω in the operating temperature range consistent with designed trace widths. This was about a factor ∼4 decrease from the measured resistance at room temperature. At the high temperature, 308K for flight and 323K for qualification, and low temperature 80K for all cables, a matrix of trace-to-trace DC electrical isolation measurements were conducted between all wire pairings. Cables which did not pass > 30MΩ isolation, only 2 of 41, were set aside. After thermal cycling flight CFC were shipped to Goddard Detector Characterization Lab (DCL) for testing with SCE and SCA. Room temperature resistance and capacitance measurement of traces relative to respective ground trace (analog or digital) were performed on receipt at DCL as an indicator of CFC health. The capacitance measurement is complementary to the isolation measurement performed at JPL.

Finally, each CFC was tested in SCS configuration with an SCA and SCE. All CFCs tested in SCS configuration passed testing requirements, namely no noise contribution or other affect could be attributed to the CFC. The SCS test most relevant to the CFC design is electrical cross talk between each of the 32 video channels. This was verified by applying a diagonal single pixel reset [7] pattern to the SCA and computing the ratio of signal in non-reset pixels in different video channels in the same row to when there is no reset pattern. More than 48 combinations of SCA, CFC and SCE were tested, all with value of cross talk at or below the lower detection limit of < 0.01% (< 100ppm) and well below the requirement of < 0.3% or 3000ppm. The largest estimated contributor to channel to channel cross talk is the SCE and is from the 22kΩ resistor bias network needed to operate the SCA in buffered mode. The series resistance and parallel capacitive impedance at the 100kHz pixel rate contributed by the CFC are 3 orders of magnitude different than the bias resistors and thus bound the CFC contribution to cross talk to < 0.1ppm.

Three qualification vibration tests were performed on early prototype CFC connected to an SCA and SCE in mock-ups of the support structure in NISP. In these tests, the dynamic environment of the CFC was approximated in order to provide confidence in the design. However, the actual levels experienced by the CFC are strongly affected by the actual movement of the
SCA and SCE in flight NISP structure. This placed a large uncertainty on the actual levels experienced by the CFC in any mock up acceptance or qualification random vibration test. Furthermore, mechanical vibration response and modal frequencies of flex cables are difficult to model. So, in place of the random vibration test and modeling, a displacement test and modal test were defined and implemented on qualification model CFCs.

For the displacement test, the CFC was configured only in the tight S in a test jig where the SCE end was fixed. The SCA end of the CFC was attached to a commercial speaker and driven by a commercial audio amplifier to an amplitude of 1mm at 20Hz. To establish baseline health of the CFC prior to the displacement cycling, a warm functional resistance measurement was conducted. The cable was first mounted in the X-Axis. The signal generator was run at 20Hz for >240mins which is long enough to exceed 288,000 cycles. This test was repeated with the CFC oriented in y and then z axes. Finally, the warm functional test was repeated on the CFC. Trace resistances were found within 1% of the pretest resistance value, well below the passing criteria of no changes greater the 10%. The same test jig was used to find the lowest modal frequencies of the CFC upto 300Hz. The model test was run in each of the 3 axes, in both tight S and loose S configurations for a total of 6 test runs. The amplitude of the drive was tuned so resonances could be seen “by eye” when recorded with high speed video. At resonance, Q values range from 30-70. The lowest measured mode frequency was at 106Hz for the loose S configuration in each of the three axes. The mode frequencies for the tight S were slightly higher for the y (118Hz) and z (111Hz) directions. The mode frequency was almost double for the tight S x (210Hz) direction as expected for motion parallel to the plane of the CFC.

Thermal conductance and thermal emissivity were measured on selected flight lot CFC. The tests were performed in a liquid nitrogen cryostat. The CFC under test was installed flat and into the test jig, figure 3, by connecting to SCA-side and SCE-side Airborn nano mating connectors each soldered into heat sink assemblies. Both the SCA-side and SCE-side connector blocks are thermally-isolated from the 77 K cold plate with gold plated Ti6-4 flexures. Both SCA-side and SCE-side thermal isolators are on separate copper plates and bolted to the liquid nitrogen cooled cold plate. Lakeshore Cryotronics DT-670 silicon diodes temperature sensors are mounted on top and bottom of the SCA and SCE side stages and monitored with an independent Lakeshore 218 temperature readout. Temperature control is achieved with Lakeshore 325 temperature controllers. The heaters on the SCA- and SCE-sides are wire-wound power resistors with nominal 25Ω resistance. At operating temperature, we measured the round trip resistance to be 26Ω for these heaters and use this value for heater resistance in power calculations to be conservative. To start the test, the article under test and the test fixture are cooled conductively, in vacuum, through the cold plate to the liquid nitrogen bath temperature at 77K. The SCA side stage \(T_{SCA}\) and SCE side stage \(T_{SCE}\) are then heated to 100 K with independent temperature control loops. The SCA base, at the cold side of the G-10 support strut is held at 77.3K, slightly above the liquid nitrogen bath temperature, with third temperature control loop. With both sides of the CFC at the same temperature, there should be zero heat flow through the cable. The required heater control power to maintain the \(T_{SCA}\) at 100 K is recorded and establishes the no-load baseline regulation power, \(P_o\) for the test. The \(T_{SCE}\) is then stepped up in temperature steps of approximately 10 K. After each temperature step and once the SCA and SCE stages reach steady state, the power, \(P_{SCA}\), required to hold the \(T_{SCA}\) at 100 K is recorded. This heater power decreases, relative to \(P_o\), by the amount of heat flowing down the CFC cable. The SCE side stage is stepped up to a maximum 142 K, \(P_{SCA}\) is recorded and then the SCE stage is re-cooled back to 100 K to confirm the \(P_o\). The measured \(P_{SCA}\) as a function of \(T_{SCE}\) are shown in figure 4 for two prototype CFCs and the flight qualification CFC. The offset in each curve is the actual difference in regulation power \(P_o\) in each test due to different thermal resistance at the bolted interfaces of the jig. The differences are the result of hand tightening the bolts.
Figure 3. CFC installed into test jig with one of two blackened emissivity plates installed below the CFC. For the thermal conductance measurement, emissivity plates are not installed.

instead of tightening to a prescribed torque using a calibrated torque wrench.

\[ P_{SCA} = P_o - G(T_{SCE} - T_{SCA}) = P_o + GT_{SCA} - GT_{SCE}. \]  

Here, \( P_o + GT_{SCA} \) and the thermal conductance, \( G \), are the offset and slope of the line fit, respectively. The data are well fit by a straight line. The values of \( G \) measured for 2 prototype and 1 qualification CFC range from \( G = 0.824 - 0.855 \text{mW/K} \). The thermal conductance computed as \( (P_{SCA}(T_{SCE} = 142K) - P_{SCA}(T_{SCE} = 100K))/42K \) is consistent with the slope of the line. The measurement precision of < 1% is based on the comparison of the values of \( P_o \) before and after the ramp of the SCE-side stage to 142K. The thermal model of the CFC included the gold over coat, copper foil wiring, constantan foil ground plane, polyimide and glue layers but not the connectors. The model predicted \( G = 1.1 \text{mW/K} \). Thus the discrepancy with the model we attribute to thermal resistance from the connectors. All systematic effects would only produce a larger thermal conductance than models, not a smaller value. Further, if there were significant radiative coupling between the SCA stage and either the SCE stage or some other source of thermal radiation that changes with \( T_{SCE} \), a higher order polynomial would improve the fit to the data, but it does not.

The test jig used for the thermal conductance measurement was adapted for the thermal emissivity measurement. The radiative heat load into the CFC and therefore into the SCA and SCE side stages is lower than the net heat loads to the SCA and SCE side stages in the thermal conductance measurement. So, the Ti6-4 flexures were replaced with lower thermal conductance G-10 fiber glass flexures covered in silvered polyester tape on the SCA and SCE side stages. This change was made so that the radiative load on the CFC in test would be a larger fraction of the total regulation power on the SCA and SCE side stages. A copper emissivity block "clam shell" was made to surround the flexible portion of the CFC mounted in the thermal conductance jig but without making physical contact to the CFC or test jig. The emissivity block consists of top and bottom plates. The inside of the two plates were blackened with Lord Aeroglaze Z306. [11, 12] This creates a thermal environment around the CFC with high emissivity. The emissivity block assembly is isolated from the LN2 cold plate with titanium flexures. All of the
Figure 4. (Left) SCA stage regulation power as a function of SCE stage temperature for 3 CFC, Teledyne 001 (squares), pathinder 001 (triangles) and flight qual 101 (circles). The slope of the linear fit is thermal conductance. (Right) $P_{CFC}$ as a function of parameter $x = \sigma A (T_{4,\text{plate}} - T_{4,CFC})$ for CFC SN 101. The slope from the linear fit is $\epsilon_{\text{eff}}$.

The exterior components of the emissivity plates are gold plated to reduce the radiative coupling of the exterior of the jig to the SCA- and SCE-sides. Resistive sheet heaters [13] were mounted on the outside of both emissivity plates to uniformly heat each plate and covered in aluminum tape to maintain the low emissivity of the exterior of the emissivity block. The slots on the two ends of the emissivity jig are made as small as possible to prevent radiation from escaping from the cavity, but not so tight that there is a risk of a touch. The interior of the cavity expands a bit on all sides to accommodate a slightly non-flat shape for the cable and the "ears" on the CFC.

The cable under test and the test fixtures are cooled by conductance to a cryostat cold plate backed by a liquid nitrogen bath. The SCA-side, SCE-side and the emissivity plates are then heated to 100 K with independent temperature control loops. With all components at the same temperature, there should be zero radiated heat exchanged between the blackened emissivity block and the cable. The heater control powers $P_{SCA}$ and $P_{SCE}$ required to maintain the $T_{SCA}$ and $T_{SCE}$ at 100 K is recorded as the no-load baseline, $P_o$. The temperature of the blackened plate is then stepped up in temperature steps of approximately 10 K until it reaches 160 K. At each temperature step, the system is allowed to settle and the values of $P_{SCA}$ and $P_{SCE}$ required to hold the $T_{SCA}$ and $T_{SCE}$ at 100 K are recorded. The temperature at the bases of the SCA and SCE side standoff are monitored to confirm these to do not change as the emissivity block temperature is increased. The sum $P_{CFC} = P_{SCA} + P_{SCE}$ decreases by the amount of heat, $Q_{CFC}$, radiatively coupled into the CFC from the warm blackened plate [14]. After the 160 K measurement, the black emissivity plates are re-cooled back to 100 K to confirm the no-load baseline $P_o$.

To convert the measured power difference into a measurement of the cable emissivity, the large parallel plate approximation is used for the radiative power, $Q_{CFC} = A \sigma \epsilon_{\text{eff}} (T_{4,\text{plate}}^4 - T_{4,CFC}^4)$, exchanged between two grey surfaces at temperatures $T_{plate}$ and $T_{CFC}$. Here $\sigma$ is Boltzmann’s constant and $A$ is the area of the flex cable within the blackened section of the emissivity plate. The area of each side of the cable is 0.00211 m$^2$ so the total area of $A = 0.00423 m^2$. The effective emissivity,

$$
\epsilon_{\text{eff}} = \frac{1}{1/\epsilon_{\text{plate}} + 1/\epsilon_{\text{CFC}} - 1}
$$

accounts for the fact that neither surface is a perfect blackbody. The measured values of $P_{CFC}$ are shown as a function of variable $x = A \sigma (T_{4,\text{plate}}^4 - T_{4,CFC}^4)$ in the right side panel in Figure 4. These data are fit to a line $P_{CFC} = P_o - Q_{CFC} = P_o - \epsilon_{\text{eff}} x$ yielding $\epsilon_{\text{eff}} = 0.0865$.
statistical error, dominated by the measurement of input power, is ±0.0001.

The test procedure was run without a cable installed to measure radiative coupling between the heated black plates and the two CFC connector mounts. The blackened emissivity block was held at only two temperature, the no-load baseline at 100 K and then at 140 K. The measured value of $Q_{CFC}$ was 2.4 mW. Although no cable was installed during the dry run, we convert this measured stray power into a parasitic emissivity by plugging in $Q_{CFC} = 2.4$ mW and $A = 0.00423\text{m}^2$ into Equation 2 and solving for $\epsilon_{eff} = 0.0362$.

The fitted value of $\epsilon_{eff}$ with the cable installed less the value with no cable, $\epsilon_{eff} = 0.0503$, is used in Equation 2 to solve for $\epsilon_{CFC}$. The emissivity of the Aeroglaze Z306, $\epsilon_{plate}$, at cryogenic temperatures in the literature vary from 0.86 to 0.91 [15, 16]. The recommended value given in the thermal engineering handbook [12] is 0.95. We compute the average value $\epsilon_{CFC} = 0.0505$ with a modelling error over the range of plate emissivity between 0.86 and 0.95 of ±0.00015. The run without a cable bounds the systematic error on measured emissivity to +0.037/−0.00. However, the upper limit is relevant only to bound worst case thermal models. The value $\epsilon_{CFC} = 0.0505$ is consistent with the thermal emissivity of 0.043 computed from the room temperature reflectance measurements. Here, the small difference in these two measurements, 0.008, is the contribution to the emissivity from the ears on the CFC which are not gold coated.

4. Conclusions
The CFC build for the Euclid project is complete. Production yield was 33 CFC acceptable for flight out of 41 starts. When operated with the Teledyne H2RG infrared detector (SCA) and cryogenic SIDECAR ASIC (SCE), the system performed as designed without additional noise attributable to the CFC and with negligible cross talk between analog or digital signal wires. Qualification model cables meet thermal cycling and handling requirements. First and second vibrational modes in both mounting configurations are 106Hz or higher. The measured thermal conductance of three different cables is <0.855 mW/K, well below the requirement of <1.5 mW/K. The thermal emissivity of the flexible section of the cable was measured to be 0.0505 meeting the requirement of <0.10.

5. References
[1] Maciaszek T et al. 2018 Proc. SPIE 9904
[2] Racca G D et al. 2016 Proc. SPIE 9904
[3] Gómez-Alvarez et al. 2018 Proc. SPIE 10707
[4] Cropper M et al. 2018 Proc. SPIE 10698
[5] Loose M, Beletic J, Garnett J and Xu M 2007 Proc. SPIE 6690
[6] Bai Y et al. 2018 Proc. SPIE 10709
[7] Waczynski A et al. 2016 Proc. SPIE 9915
[8] Barbier R et al. 2018 Proc. SPIE 10709
[9] 2009 IPC-6013 IPC Subscription
[10] 2015 J-STD-001FS
[11] Socomore Company Aeroglaze Z306 polyurethane coating
[12] Gilmore D G (ed) 2002 Spacecraft Thermal Control Handbook vol 1, The Aerospace Press and AIAA Inc.
[13] All Flex Inc 2019 Polyimide heater
[14] Tuttle J et al. 2016 Cryogenics 74 166 – 171
[15] Bass M and Optical Society of America 1994 Handbook of Optics: Fundamentals, techniques, and design (Handbook of Optics no v. 1) (McGraw-Hill) ISBN 9780070477407
[16] Persky M 1999 Rev. Sci. Inst. 70 2193–2217

Acknowledgements
Work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration. ©2019 California Institute of Technology. Government sponsorship acknowledged.