Design of an efficient broadband far-infrared Fourier-transform spectrometer

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As part of a feasibility study for a far-infrared Fourier-transform spaceborne spectrometer, the criteria that drive the choice of the instrument configuration have been identified as broadband operation, dual input and output ports, optics of the interferometer with full tilt compensation, and measurement of both planes of polarization of the source on a single detector. Despite the fact that some of these requirements are apparently difficult to reconcile, a new configuration of the polarizing interferometer that meets all the above requirements has been identified. The considerations that led to the design of this new configuration are discussed.

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1. Introduction

A feasibility study was recently conducted for a Fourier-transform spectrometer (FTS), named the radiation explorer in the far infrared (REFIR), aimed at the observation of the Earth's emission spectrum from space. The design of the optical configuration of this instrument is discussed here, with a review of the instruments that have been either employed or considered for similar space applications and of the configurations that are possible in the far-infrared spectral region.

For broadband operation in the far infrared, a constant efficiency is offered by a polarizing interferometer, such as the Martin–Puplett type,[1] which uses a polarizer as a beam splitter (BS). At long wavelengths, polarizing grids perform as almost perfect polarizers and are limited at long wavelengths only by the size of the optical components and at short wavelengths only by the period of the grids. The relevance of this property was recently further augmented by the development of high-precision photolithographic polarizers[2] that can be used up to 1000 cm^{-1}.[3] Furthermore, the polarizing interferometer offers the important advantage of dual input and dual output, which is a valuable feature for making accurate radiometric measurements.

Possible drawbacks of the polarizing interferometer in its classic configuration are its exploitation of only a fraction of the source signal, because it measures one polarized component of the beam, and its incompatibility with fully tilt-compensated optics owing to the use of rooftop mirrors in the two arms of the interferometer.

In this paper we describe a new optical configuration that combines all the features of a classic polarizing interferometer (i.e., broad band, high efficiency, and dual input and output ports) with total signal exploitation and full tilt compensation. The new configuration meets all the instrument requirements established for the REFIR project and, to our knowledge, is innovative in the sense that no optical configuration that combines all these properties in a compact instrument has been proposed so far. In Section 2 we briefly recall the scientific requirements of the REFIR instrument. In Section 3 a few relevant FTS instruments considered for space applications are briefly shown, and their properties are compared with REFIR requirements. Finally, in Section 4 the possible configurations of the polarizing interferometer are reviewed and the considerations that led to the selection of the new configuration are described.

2. Scientific Objectives and Instrument Requirements

Climate research is one of the most challenging and important problems facing humankind today. The

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importance to worldwide economies and industries of even the smallest climate change or trend is potentially huge.

Against this background, the main scientific objectives of the REFIR project are

to monitor a portion of the planetary emission to space that is not covered by any current or planned mission/instrument and

to improve our knowledge of the distribution of middle and upper tropospheric water vapor, using the strong spectral signature of water vapor in the far infrared.

The operation from space of the REFIR instrument would fill a gap in knowledge and therefore contribute in an important way to existing space programs.

The space operation and these scientific objectives require a small and reliable instrument with high performance over a broad spectral interval. In particular, the instrument requirement is continuous operation at 100–1000-cm^{-1} with a spectral resolution of 0.5 cm^{-1}. Accuracy of the radiometric calibration requires dual input and output in the instrument and the acquisition of dual-sided interferograms with known phase between subsequent interferograms. Space operation requires detectors with moderate cooling and simple and reliable mechanisms. To meet the lifetime requirements, the interferometric alignment is preferentially provided by a tilt-compensated optical configuration rather than by mechanical accuracy of the driver. Less stringent requirements apply for shear compensation because only one on-axis detector is used in the focal plane.

3. Space Fourier-Transform Spectrometer Instrumentation

A general requirement of FTS instruments that is particularly important in space applications is freedom from mechanical errors, which are difficult to avoid in mechanical movements that need to operate reliably and for long times in difficult environments. To this purpose compensation for tilt and shear errors of the moving mirrors is the most important feature of an instrument selected for space operations.

An atmospheric trace molecular spectrometer[4] called ATMOS is a high-resolution middle-infrared FTS that has been operated in a few flights on the Space Shuttle for the study of the Earth's atmosphere by the technique of solar occultation. This instrument uses a cunning optical configuration that is fully compensated for tilt and shear errors. However, this configuration does not provide separate inputs and outputs, which are not necessary for an instrument that observes an intense source but would be important for emission measurements, as in the case of the REFIR.

Also, some space instruments that have been designed for emission measurements, such as the interferometric monitor for greenhouses gases[5] (IMG)

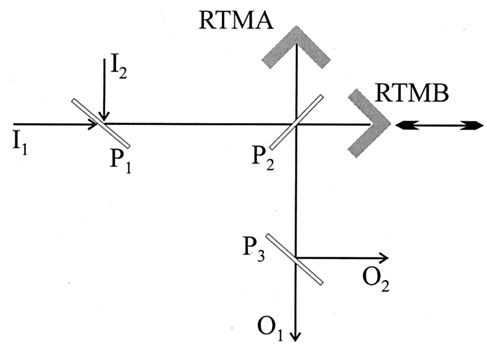

Fig. 1. Optical layout of a polarizing interferometer in the classic configuration (Martin–Puplett type). Abbreviations used in this and subsequent figures are defined in the text.

and the improved Infrared Atmospheric Sounding Interferometer[6] (IASI), do not have separate inputs and outputs, but others, such as the Michelson interferometer for passive atmospheric sounding[7,8] (MIPAS) and the Tropospheric Emission Spectrometer[9] (TES) do have separate inputs and outputs as well as full tilt-compensated reflectors. None of them has shear compensation, but this is considered a less important requirement. All these emission instruments can operate only in the high-frequency part of the Earth's emission spectrum, which is required for the REFIR experiment, because the optical components of these instruments, the BS in particular, cannot operate at frequencies below 600 cm^{-1}.

A space FTS that can operate at long wavelengths is the far-infrared absolute spectrophotometer[10] (FIRAS). This instrument operated onboard the Cosmic Background Explorer satellite and provided observations of the cosmic background in the 1–100-cm^{-1} range with high radiometric accuracy. This instrument uses a polarizing BS and has the classic configuration of the polarizing interferometer. However, as we mentioned in Section 1, this configuration has the shortcomings of being able to exploit only half of the source signal and of incompatibility with fully tilt-compensated optics. These shortcomings imply a loss factor of 2 in instrument efficiency and difficult mechanical requirements if the highest frequency of the instrument is extended from the 100 cm^{-1} of the FIRAS to the 1000 cm^{-1} required for the REFIR.

4. Instrument Configuration

A. Classic Polarizing Interferometer

The optical layout of the polarizing interferometer in its classic configuration, as devised by Martin and Puplett in 1969,[1] is shown in Fig. 1. The principle of operation of the instrument is briefly recalled here.

The input polarizer (P_1) transmits the vertical plane of polarization of the analyzed source (I_1) and reflects the horizontal plane of polarization of a reference source (I_2). The two sources make up the two input

Table 1. Properties of FT Spectrometers As a Function of the Type of Optics Employed in Each Interferometric Arm

Type of Optics in the Interferometric Arm	Moving Part	Number of Degrees of Tilt Compensation	Number of Degrees of Shear Compensation	Number of Reflections	Folding of Wave Front
Plane mirror	Plane mirror	0	2	1	None
Rooftop mirror	Rooftop mirror	1	1	2	About one axis
Cube corner	Cube corner	2	0	3	About one point
Cat's eye	Cat's eye	2	0	3	About one point
Two perpendicular rooftop mirrors	One rooftop mirror	2	1	6	About one axis
Cube corner and flat mirror	Cube corner	2	2	7	None

ports of the instrument. Polarizing BS P_2 has its principal axis oriented at 45° with respect to the directions of polarization of the two sources. Therefore each source is split into two polarized components (parallel and perpendicular to the principal axis of the BS) of equal amplitude, which enter the two arms of the interferometer. A rooftop mirror (RTMA for arm A and RTMB for arm B; see Fig. 1) in each arm of the interfermoter reflects the beam back from that arm and introduces a folding of the wave front about the dihedral edge of the roof. The dihedral edge of each fixed roof is vertical, so for a wave polarized at $\pm 45°$ the folding of the wave front about a vertical axis is equivalent to a rotation of the plane of polarization by 90°. When the polarized components return to the BS after traveling different optical paths, the one that was originally transmitted is now reflected and the one that was reflected is now transmitted. For an ideal polarizing BS the full input signal is transmitted to the output side. Nevertheless the components that traveled different paths do not interfere because they have perpendicular polarizations.

The output polarizer (P_3) has its principal axis oriented at 45° with respect to that of the BS (i.e., either parallel or perpendicular to that of the input polarizer) and creates two outputs (transmitted and reflected beams O_1 and O_2, respectively) in which the components that traveled different paths now have the same polarization and can interfere to produce interferograms. At both output ports we observe the interferogram of the spectral difference between the two input ports. The two interferograms have opposite phase.

This optical configuration provides two inputs and two outputs, measures only one plane of polarization of the analyzed source, and uses in the two arms of the interferometer rooftop mirrors that are partially compensated for tilt in the plane perpendicular to the roof edge.

A full analysis of the polarizing interferometer is provided in Ref. 11.

B. Tilt and Shear Compensation

The amplitude of the interferometric modulation depends on the quality of the optical alignment between the two interfering wave fronts in terms of tilt and lateral shift (shear). To maintain the quality of the optical alignment during the interferometric scan one must use either highly accurate scanning mechanisms or an optical layout in which tilt and shear of the returning beam are unaffected by inaccuracies in the movement (tilt and shear compensation).

Tilt and shear compensation are an important consideration for accurate measurements coupled to long lifetime operation. Table 1 summarizes some of the most common mirror combinations that have been used in the arm of an interferometer.[12] In some cases the optics is simple and all the optical components are moved to vary the path difference; in other cases only a subset of the optical components is moved. The moving part is identified in the second column. Tilt and shear can be compensated for in either one or two directions. The number of compensated directions is given in columns 3 and 4, respectively, for tilt and shear. Tilt compensation is usually more important than shear compensation. The optics can provide either a mirror reflection in which each point of the wave front returns on itself or some folding of the wave front (about either an axis or a point). The type of folding of the wave front is identified in column 6 of the table.

Only folding about one axis can provide the rotation of the direction of polarization, which is used in the classical configuration of the polarizing interferometer. Therefore only a subset of the types of optics listed in Table 1 is compatible with the rotation of the plane of polarization used in the classic polarizing interferometer. To consider the use of the other types of optics, one must consider a modified polarizing interferometer.

Figure 2 shows a polarizing interferometer with flat mirrors (MA and MB).[13] Because the flat mirrors do not rotate the plane of polarization of the beams traveling in the two arms of the interferometer, when the beams recombine on the BS they are transmitted and reflected back to the input. In this case one of the two ports of the input polarizer must be used for the detector; it therefore becomes an output and is no longer

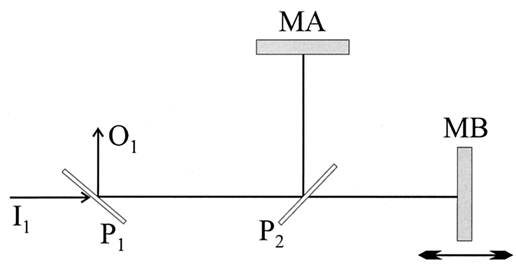

Fig. 2. Polarizing interferometer with flat mirrors.

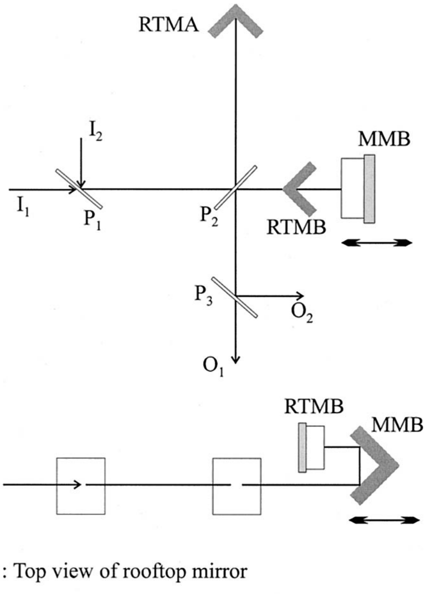

Fig. 3. Double input–output polarizing interferometer with dual rooftop mirrors for tilt compensation.

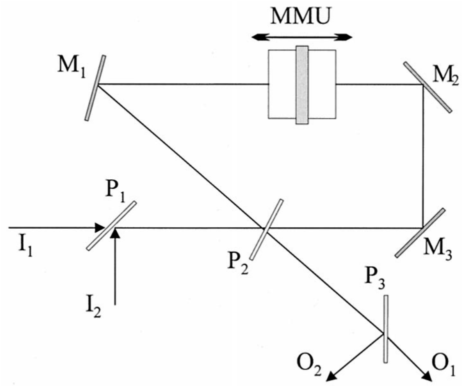

Fig. 4. Second configuration of a double input–output polarizing instrument with tilt compensation.

available as an input. Similarly, the second output port travels toward the source and can no longer be used to position a second detector. This instrument configuration is compact, but the dual input–output feature is lost. Furthermore, no tilt compensation is obtained with flat mirrors. This configuration does not have the required properties but shows that the polarizing interferometer does not necessarily depend on the use of rooftop mirrors.

Moreover, the use of cube-corner and cat's-eye mirrors, which provide the required tilt compensation and could be used to attain dual input and output ports (see Subsection 4.D below), is in principle possible with the optical configuration of Fig. 2, even if this has not been reported in the literature. The reason for the lack of success of these optical components in a polarizing interferometer is probably to be found in the fact that they are expected to spoil the status of linear polarization of the beam, leading to complex effects that may be difficult to control in a polarizing interferometer.

From Table 1 it follows that the only clean solution for tilt compensation in both axes is that of a dual-rooftop mirror,[14] which is compatible with the rotation of the plane of polarization. The instrument layout, shown in Fig. 3, is similar to that of the classic polarizing interferometer. The only difference is that the path difference delay is introduced not by the movement of the rooftop mirror (RTMB in Fig. 3), which rotates the plane of polarization, but by the movement of a folding rooftop mirror (MMB, moving mirror in path B) added to the layout. This optics provides full tilt compensation without compromising the dual input–output feature.

The optics that are listed in Table 1 implement the compensation within one arm of the interferometer. A further degree of freedom that can be explored for the attainment of tilt compensation is that of overall compensation in the two arms of the interferometer with a single movement that introduces an equal tilt in the two arms. Figure 4 shows a solution of this type.[15] The two rooftop mirrors in the two arms of the interferometer are part of a solid unit (MMU). The movement of this unit increases the path difference in one arm while decreasing it in the other arm. Tilt of this unit in the plane perpendicular to the dihedral edge is compensated for by the rooftop mirrors. In the plane parallel to the dihedral edge the two beams are affected by an equal tilt, because the two back-to-back rooftop mirrors are part of the same optical unit, with a resulting relative compensation when they recombine on the BS. To this purpose the different numbers of reflections in the two arms of the interferometer ensure that the two beams are tilted by the same angle and in the same direction when they recombine on the BS. The two configurations of Fig. 3 and 4 provide full tilt compensation without losing the feature of dual input–output.

C. Total Signal

Only one plane of polarization of the source is used in all the configurations considered in Figs. 1–4. A second important issue is the measurement of both planes of polarization of the source with the same detector.

Figure 5 shows an optical configuration that uses both planes of polarization in an interferometer with a polarizing BS. In this configuration, which was analyzed in Ref. 16 and was implemented in the instrument described in Ref. 17, the signals that in the classic configuration are wasted at the input polarizer are recovered and fed into the BS as well. In this way the input polarizer conditions two beams. The first beam is folded into the BS by mirror M_1 and exits from the BS on the M_2 side. Mirror M_2 folds this output on the input polarizer, which at this point operates as an output polarizer. The second beam is folded into the BS by mirror M_2 and exits from the BS on the M_1 side. Mirror M_1 folds this output on the input polarizer, which again operates as an output polarizer. With this configuration one of the two input ports must be used to position a detector and therefore becomes an output; therefore the dual input–output feature is lost.

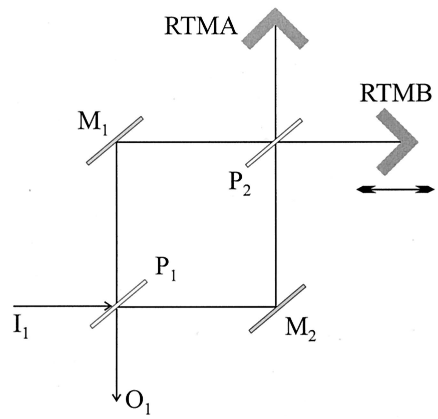

Fig. 5. Configuration with double signal and single input–output.

It is important to stress that the advantage of the configuration of Fig. 5 is not just the use of the second plane of polarization of the source (which in principle can always be sent to a second spectrometer) but its measurement on the existing detector with no extra measurement noise (in the case of detector-noise-limited measurements).

The configuration of Fig. 5, which has been introduced as a modification of the classic polarizing interferometer of Fig. 1, can also be implemented as a modification of the configuration of Fig. 2, which uses plane mirrors. In this case the beam that reaches beam splitter P_2 on the M_1 side returns back on M_1, the beam that reaches beam splitter P_2 on the M_2 side returns back on M_2, and the instrument operation does not depend on the rotation introduced by the rooftop mirrors.

D. Dual Input and Output

In the configurations of Figs. 2 and 5 the dual input–output feature was lost; it is therefore important to identify how this feature can be regained.

In an interferometer using an amplitude BS, the outputs can be separated from the inputs by means of a lateral offset between the incoming and the returning beams. The offset is easily obtained with any optical arrangement that has either an axis or a point of folding (see Table 1) located outside the beam. The same approach can be adopted in the case of an instrument with a polarizing BS. (The configurations that can provide a separation of input and output ports in the polarizing interferometer are described in Ref. 12.) A configuration that regains the dual input–output feature in a polarizing interferometer that measures the total signal is described in Ref. 11.

The creation of separate input–output ports by means of a lateral offset between the input and output beams has the advantage of making impossible any spurious contribution of the radiance that enters the interferometer from the output ports to the observed signal, as may occur instead in the case of separate input–output ports obtained with a selection among different polarizations.

Table 2. Properties of Various Instrument Configurations

Configuration	Tilt Compensation	Dual Input and Output Ports	Detection of Total Signal
Fig. 1		√	
Fig. 2			
Fig. 3	√	√	
Fig. 4	√	√	
Fig. 5			√
Fig. 6	√	√	√

E. Selected Configuration

With reference to Table 2, in which the properties of the relevant configurations presented in Figs. 1–5 are summarized, we notice that the three main requirements (tilt compensation, dual input and output ports, and total signal detection) can all be met individually. The problem is to identify a configuration that can meet the three requirements simultaneously.

We find that the desired properties can be combined in a single instrument with the optical configuration shown in Fig. 6. The instrument is built on two floors that have equal optical components. The optical components in the two floors, apart from the input polarizer located on the lower floor and the output polarizer located on the upper floor, are merged into a single component. The beams go from the lower floor to the upper floor by way of the two rooftop mirrors (RTMA and RTMB), which are part of a solid unit that provides the interferometric sweep.

The alignment is compensated for tilt in both directions and for shear in one direction. The shear compensation implies that the scanning mechanism does not necessarily need to provide a translation along a straight line, and a translation along a curved line is also acceptable.

The polarizing BS can be oriented with the principal axis either at 45° from the dihedral edge of the rooftop mirror (as in the configuration of Fig. 1) or orthogonal to it. We prefer the second option, such that the polarization in the interferometer is always either parallel or perpendicular to the plane of inci-

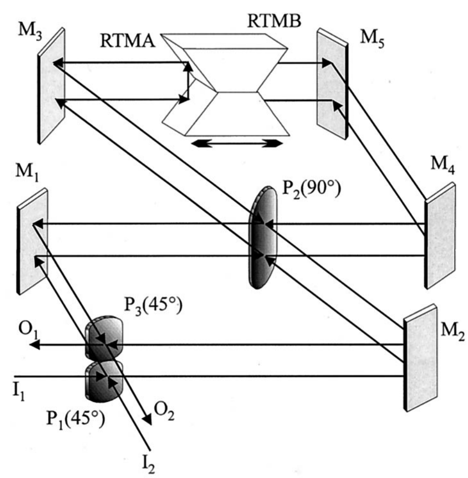

Fig. 6. Proposed configuration of double input–output polarizing interferometer with double signal and tilt compensation.

dence for all reflections. Therefore the beam that enters the BS on either side will exit, on a different floor, from the same side.

The interference may depend not only on the path difference between the two arms of the interferometer but also on the path difference between the two paths that include mirrors M_1 and M_2. An asymmetry as well as a small misalignment are introduced on purpose between these two paths to ensure that the residual coherence does not lead to measurable interference. With a low-resolution instrument, as in the case of the REFIR, this condition can be reached easily with an asymmetry of a few centimeters between the two paths. The optical layout also permits the compensation of eventual deviations of RTMA and RTMB from perfect 90° rooftops. To this end, polarizing beam splitter P_2 should be made from two separate units. The relative orientation of these two units can be used for the correction. In this way, the wave fronts can be made parallel when they are recombined on the output polarizer.

5. Conclusions

A new optical configuration for a polarizing interferometer has been identified that provides all the following desirable features:

(1) Broadband spectral coverage,
(2) Separate input and output ports,
(3) Tilt compensation in both directions of the wave front of possible mechanical error of the moving unit, and
(4) Measurement of both planes of polarization of the source without an increase in the detector throughput.

Each of the last two features, which are not provided by the classic configuration of the polarizing interferometer, is obtained at the cost of an increase in the optical path of the instrument. In an instrument with a large solid angle, as in a low-resolution FTS, the path increase also implies an increased spread of the beam. For the REFIR instrument this is a price that is well justified by the importance of the two requirements.

More generally, the analysis of the possible options has shown that, whereas the first feature depends only on the choice of the BS, the other three depend on the optical configuration. Only a few examples of the most instructive configurations have been presented, but it is possible to verify that configurations can be identified that meet any combination of the last three requirements. Therefore, because each of those three requirements is met at the cost of some increase in instrument size, the required combination must be selected as a compromise between volume and performance.

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References

1. D. H. Martin and E. Puplett, "Polarised interferometric spectrometry for the millimetre and submillimetre spectrum," Infrared Phys. **10,** 105–109 (1969).
2. J. P. Auton, "Infrared transmission polarizers by photolithography," Appl. Opt. **6,** 1023–1027 (1967).
3. P. A. R. Ade, Department of Physics, Queen Mary & Westfield College, Mile End Road, London E1 4NS, UK (personal communication, 1997).
4. I. R. Abel, B. R. Reynolds, J. B. Breckinridge, and J. Pritchard, "Optical design of the ATMOS Fourier transform spectrometer," in *Optical System Engineering*, P. R. Yoder, ed., Proc. SPIE **193,** 12–26 (1979).
5. H. Shimoda and T. Ogawa, "Interferometric monitor for greenhouse gases (IMG)," in *Infrared Spaceborne Remote Sensing II*, M. S. Scholl ed., Proc. SPIE **2268,** 92–102 (1994).
6. P. Javelle and F. Cayla, "Infrared atmospheric sounding interferometer—instrument overview," in *Space Optics 1994: Earth Observation and Astronomy*, G. Cerrutti-Maori and P. Roussel, eds., Proc. SPIE **2209,** 14–23 (1994).
7. M. Endemann, G. Lange, and B. Fladt, "MIPAS for Envisat-1," in *Space Optics 1994: Earth Observation and Astronomy*, G. Cerrutti-Maori and P. Roussel, eds., Proc. SPIE **2209,** 36–47 (1994).
8. H. Fischer and H. Oelhaf, "Remote sensing of the vertical profiles of atmospheric trace constituents with MIPAS limb-emission spectrometers," Appl. Opt. **35,** 2787–2796 (1996).
9. R. Beer and T. A. Glavich, "Remote sensing of the troposphere by infrared emission spectroscopy," in *Advanced Optical Instrumentation for Remote Sensing of the Earth's Surface from Space*, G. Duchossois, F. L. Herr, and R. Zander, eds., Proc. SPIE **1129,** 42–51 (1989).
10. J. C. Mather, D. J. Fixsen, and R. A. Shafer, "Design for the COBE far infrared absolute spectrophotometer (FIRAS)," in *Infrared Spaceborne Remote Sensing*, M. S. Scholl, ed., Proc. SPIE **2019,** 168–179 (1993).
11. D. H. Martin, "Polarizing (Martin–Puplett) interferometric spectrometer for the near-and submillimeter spectra," in *Infrared and Millimeter Waves*, K. J. Button, ed. (Academic, New York, 1982), Vol. 6, Chap. 2, pp. 65–148.
12. B. Carli, "High-resolution far-infrared FT spectroscopy of the stratosphere: optimization of the optical design of the instrument," in *7th International Conference on Fourier Transform Spectroscopy*, D. G. Cameron, ed., Proc. SPIE **1145,** 93–98 (1989).
13. A. E. Costley and J. Chamberlain, "Measurement of the emission from a time-varying plasma at millimetre and submillimetre wavelengths," in *Proceedings of the Conference on Precision Electromagnetic Measurements*, IEE Conference Publ. **113,** 210–212 (1974).
14. B. Carli, P. A. R. Ade, U. Cortesi, P. Dickinson, M. Epifani, F. C. Gannaway, A. Gignoli, C. Keim, C. Lee, C. Meny, J. Leotin, F. Mencaraglia, A. G. Murray, I. G. Nolt, and M. Ridolfi, "SAFIRE-A spectroscopy of the atmosphere using far-infrared emission/airborne," J. Atmos. Ocean. Technol. (to be published).
15. H. L. Buijs and H. P. Gush, "High resolution Fourier transform spectroscopy," J. Phys. C2 **28,** 105–108 (1967).
16. B. Carli and F. Mencaraglia, "Signal doubling in the Martin–Puplett interferometer," Int. J. Infrared Millimeter Waves **2,** 1045–1051 (1981).
17. S. Aiello, A. Barbis, A. Bonetti, V. Natale, G. Valmori, and G. Ventura, "A high efficiency polarizing interferometer for astronomical observations in the submillimetric region," Infrared Phys. **26,** 347–352 (1986).