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Final Report to the
National Aeronautics and Space Administration,
Marshall Space Flight Center,

on

Wavelength-Tunable Liquid Crystal Imaging Filters for Remote Sensing From Geosynchronous Platforms

(P.O. H-11987D)

from

Cambridge Research and Instrumentation, Inc.
21 Erie Street, Cambridge, Massachusetts, 02139
Telephone: (617) 491-2627

Principal Investigator

Name: Peter Foukal
Title: President
Signature: Peter Foukal
Date: October 22, 1992

Abstract

Recent advances in liquid crystal technology have enabled us to construct tunable birefringent filters with bandwidths between approximately 0.1 nm and 50 nm. The center wavelength of these filters can be selected electronically, in a few tens of milliseconds, with no moving parts.

These liquid crystal tunable filters (LCTF's), together with existing CCD detectors, make possible a new generation of lightweight, rugged, high-resolution imaging spectrophotometers. Such instruments would be particularly interesting for remote sensing applications from geosynchronous platforms. Important advantages exist in the aperture, absence of image shift, power consumption, size, weight, and absence of high drive frequencies, compared to current instruments used or considered for multispectral scene analysis.

In the present work we have reviewed spectral requirements of planned NASA geosynchronous remote sensing missions, and identified several applications of the liquid crystal tunable filter technology. We have modelled the LCTF performance in the visible and near-infrared, and carried out a literature study on space-hardening of the filter components, to evaluate the suitability of LCTF's for geosynchronous missions. We have also compared the power consumption, weight, size, reliability, and optical performance of an imaging spectrophotometer using a LCTF monochromator, to other instruments that have been put forward for remote sensing from geosynchronous platforms.

We put forward some conceptual designs for LCTF's that seem to offer important advantages in wavelength-flexibility, tuning speed, power consumption and reliability, over the mechanical filter wheels presently baselined for the HEPI and ALM experiments. The extremely wide acceptance angle achievable with LCTF's could also avoid the present need for large-aperture interference filters in the ALM (and LIS) experiments. Thermal vacuum testing and radiation damage analysis will be required to investigate the space hardening of these new filters for geosynchronous flight.

1. Introduction

This report describes a new type of optical filter developed at CRI, Inc., that is electro-optically tunable in wavelength over hundreds of nanometers, in tens of milliseconds, with no moving parts. When used together with the 2-D detector arrays now available, this new kind of filter could form the basis of a new generation of compact imaging spectrometers for remote sensing in the visible and IR spectral regions. The low power consumption, low voltages, absence of moving parts, and versatile optical performance of these filters make them of particular interest for remote sensing from geosynchronous platforms.

The past decade has witnessed substantial advances in detector technology. Greatly improved CCD cameras and image processing hardware and software have become available, giving real-time access to 2-D imaging data and affording greater interactive control over data-taking. Until now, no comparable advance has been made in filter or monochromator technology. Imaging spectrometers still rely mainly on cumbersome, mechanical filter wheels with limited passband choices. Grating monochromator systems can be advantageous when hundreds of strictly simultaneous spectral channels are required, but the advantages of multi-spectral framing cameras have not yet been fully realized because of the wavelength tuning limitations.

The present report seeks to expand these horizons by exploring the use of a new type of tunable filter using advances in liquid crystal technology. Depending upon the design, these filters can be broad band (50 nm or more), moderate band (1 - 2 nm), or extremely narrow-band (< 0.05 nm). The technology is based on Lyot birefringent filters, which have long been used for their narrow passbands and excellent uniformity across the field of view[1]; the innovation is the development of tunable versions of these devices, which use nematic liquid crystal elements as the tuning elements. Tuning is rapid (a few tens of milliseconds) and requires no moving parts. Important proprietary advances in the sensing and control of the filter passband position have been made at CRI, Inc.[2,3] (further patents pending). A reproducibly tunable filter of this type offers great potential as the basis for a high-resolution imaging spectrometer, particularly when real-time control of the observing program is required.

Attempts have been made to develop new filter technologies, such as tunable imaging etalons[4] and acousto-optic tunable filters (AOTF's)[5]. Imaging etalons of adequate aperture (more than a few mm) are delicate instruments that require alignment servos to maintain plate parallelism. AOTF's require unwieldy controllers and exhibit relatively strong sidebands. However, it appears possible to make excellent tunable filters in a much less demanding way. Advances in liquid crystal materials and devices now open up the possibility of building upon some of the fabrication techniques developed over the past fifty years in making birefringent filters. This will yield tunable filters for a wide range of uses in remote sensing and in many other research and commercial applications. The tunable filters we describe do not require high drive frequencies, and offer low power dissipation.

In this report we describe LCTF's we have constructed at CRI, Inc., which exhibit very promising imaging quality, spectral rejection and stability in the visible and near-IR wavelength ranges. Liquid crystal mixtures now available exhibit greatly enhanced stability under aging, temperature cycling, water attack, and UV exposure, encouraging us to study LCTF's as to their field-worthiness in remote sensing applications.. The overall aim of this study is to investigate the suitability of these compact, lightweight new imaging filters for use as monochromators in NASA remote sensing from geosynchronous platforms.

2. The Technical Objectives of This Study are Stated as Follows:

i) To review the requirements on spectral and optical performance of imaging spectrophotometers planned for remote sensing from NASA geosynchronous platforms. Thus to identify suitable applications for LCTF monochromators on such NASA platforms.

ii) To model (and measure where possible) the visible and IR-range performance of LCTF's for comparison with performance of other monochromators such as mechnical filter wheels, AOTF's and gratings used or being considered for NASA remote sensing applications.

iii) To evaluate the mechanical (size, weight, geometry, etc) and electrical (power consumption, frequencies, voltages, etc) properties of LCTF's and their overall potential for reliability and space hardening, and compare these properties with those of other monochromators considered for remote sensing from geosynchronous applications.

iv) To provide a conceptual model for one or more LCTF monochromators for remote sensing applications identified above.

v) To provide a verbal presentation on our findings to MSFC personnel, and also to provide a written report stating our methods, findings and recommendations.

3. Review of GEO Instruments

We first reviewed NASA plans for remote sensing from geosynchronous orbit. Documents used included the MSFC Preliminary Definition Study "Geostationary Earth Observatory", the document "Earth Orbiting Technologies for Understanding Global Change" (Harris et al. IAF-89-001), the conceptual design study "Geostationary Earth Processes Spectrometer" (Final report to Contract NAS8-38175), and the Phase A instrument studies, "Geostationary Imager Concept Development", "A High Resolution Earth Process Imager for the Earth Sciences Geostationary Platform", "Geostationary Earth Climate Sensor", and "The Geo Platform High-Resolution Interferometer Sounder".

Information in these documents was used to identify the needs for spectral imaging in remote sensing from geosynchronous platforms. Of particular interest are requirements on wavelength range, passband widths, spectral purity, field of view, scan rate, size, power, etc, posed by the planned remote sensing observations. We used these documents and discussions with JPL staff involved in the HEPI Phase A Study (Frank Wright, Kirk Seaman, Valerie Duval), to determine other aspects of the required monochromator optical performance, such as angular resolution, uniformity, transmission etc, in the required spectral regions.

For the purpose of our review, we next grouped the GEO instruments into four categories. The first consisted of those for which an obvious and direct application of the LCTF could be envisioned. The second included those instruments whose science objectives were consistent with possible use of the LCTF, but significant changes in the existing design would be required to employ the LCTF technology. In the third were instruments with no application for the LCTF. The fourth category included instruments for which insufficient information was available to decide on the possible application of the LCTF.

In the first category, we placed the High Resolution Earth Processes Imager (HEPI) and the Advanced Lightning Mapper (ALM). These instruments are described in more detail below. In the second we placed the Geo-Stationary Earth Processes Spectrometer (GEPS), the Geostationary Atmospheric Profiler (GAP), and the Trace Gas Imager (GTCI). In the third we placed the Geostationary Microwave Precipitation Radiometer (GMPR) and the Solar Constant Monitor (STIM). The NOAA Operational Instruments proposed for GEO were not well enough defined by the documents at our disposal, to judge the potential applications to the LCTF technology. It is possible that the operational imager, and perhaps also the sounder and the space environmental monitor, could benefit from the LCTF approach.

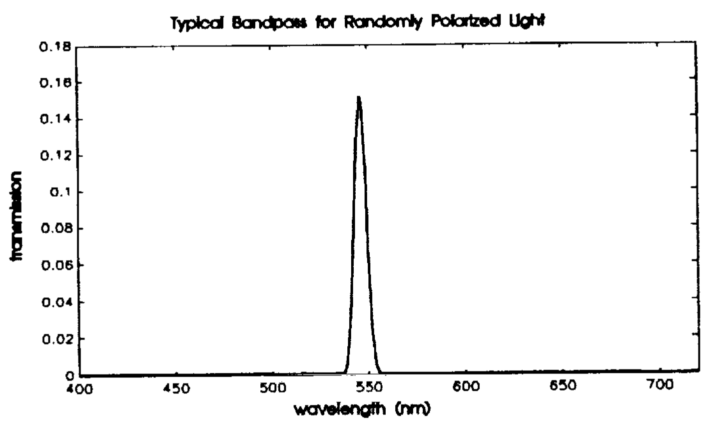
Both HEPI and ALM seem well suited to application of the LCTF. As presently configured, HEPI is to use three filter wheels, each provided with 5-12 filters. As described in Section 7 below, the visible and IR-range wheels could be replaced by two LCTF's, although imaging in the UV region (below 400 nm) could not be handled with an LCTF in the present state of technology, so a filter wheel would still be required in that wavelength region. Our recent finding that LCTF's can be built with extremely wide acceptance angles leads us to suggest an interesting application of this useful property to the ALM experiment.

4. Description of LCTF Performance in the Visible and Near-IR

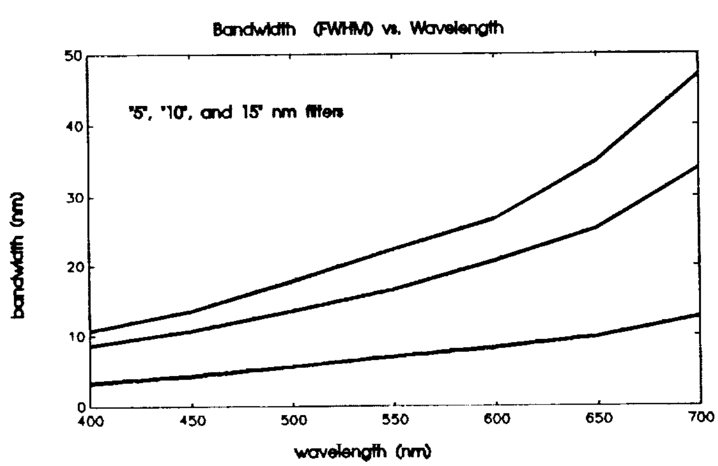
a) Wavelength Range

Our investigation of liquid crystal and polarizer properties in the visible and near-IR indicates that the useful ranges of LCTF imaging operation, using our Lyot-type design with materials available at the present time, are 400 - 750 nm, 0.7μ - 1.7μ, and 1.1μ - 2.3μ. Our models indicate that operation between 330 nm and 390 nm in the UV should be feasible using a modified design, but imaging quality at those wavelengths would be compromised. In the IR our modelling indicates a design change to a birefringent Fabry-Perot cavity should provide good imaging performance to beyond 6μ, although the 3.4 - 3.65μ region is not accessible at present because of liquid crystal material absorption in that range.

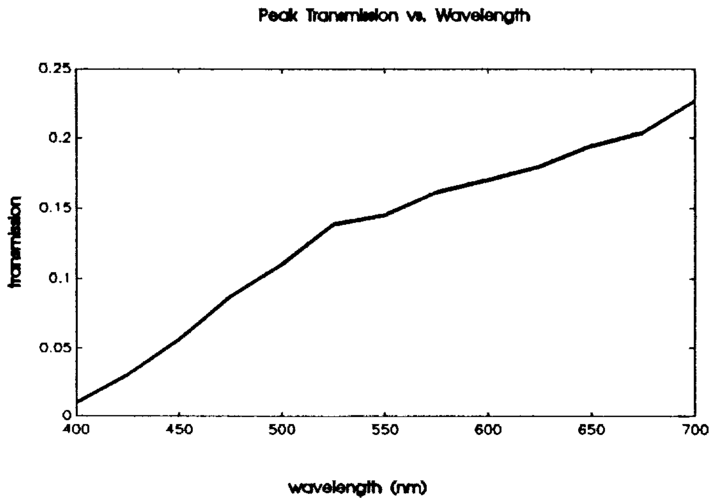
b) Bandpass



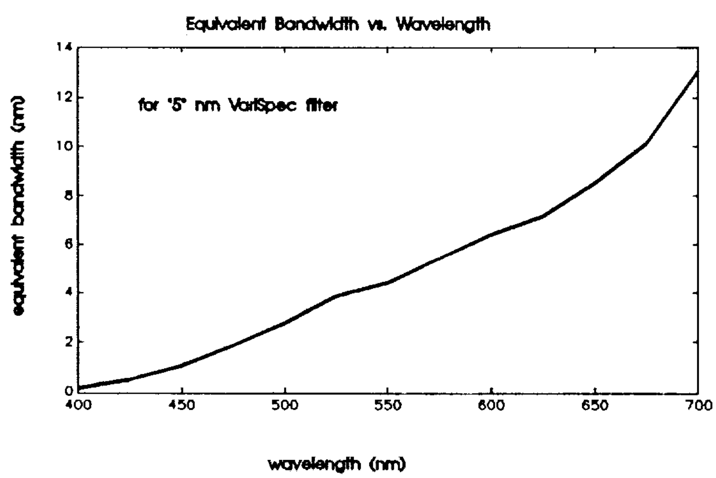
The measured shape of the bandpass for an LCTF filter of 10 nm FWHM is shown in Fig 1. The width at a given wavelength is specified at the time of construction. Its variation with wavelength for filters of nominally 5, 10, and 15 nm passband widths, is shown in Fig 2. This variation of the passband width behaves approximately as λ^2.



c) Transmission

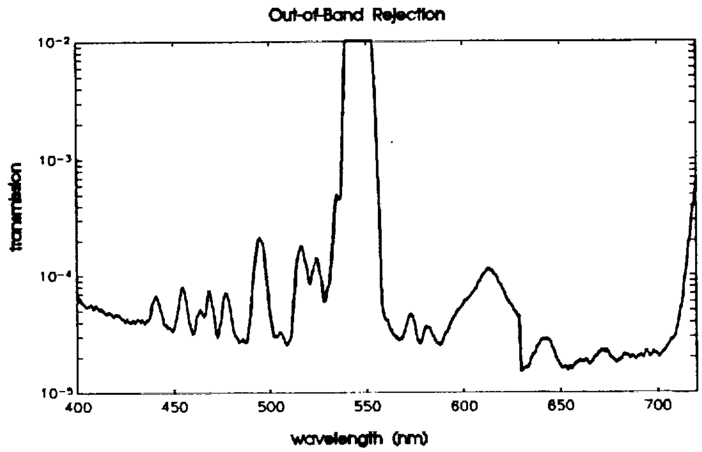


The dependence of peak transmission upon wavelength is shown in Fig 3, for randomly polarized light. Curve (a) shows measured values for a filter of 5 nm passband width. Transmission is low (a few percent) in the blue, and increases to 20% around 700 nm for this 10-stage filter. Significantly higher values of transmission are obtained for filters with fewer elements. A six-element filter of 50 nm passband, for instance, has a measured peak transmission of 14% at 450 nm, rising to over 25% at 650 nm.



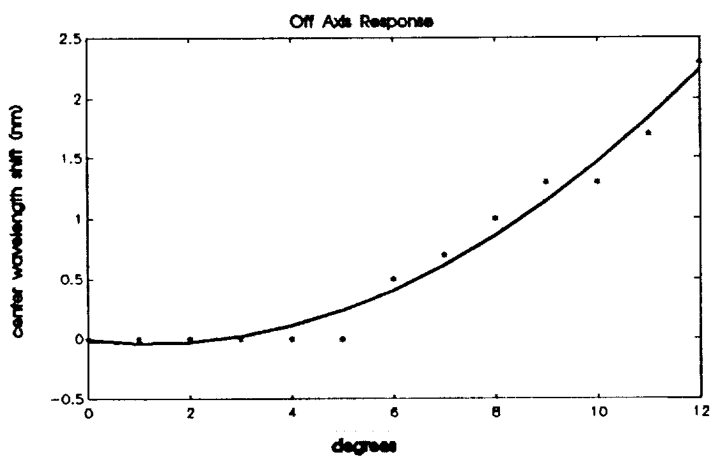
For a tunable filter whose passband and peak transmission change with wavelength, it is useful to define an "equivalent bandwidth". This is the bandwidth of a filter having the same throughput at each wavelength as the actual filter, but assumed to have constant transmission. We expect this equivalent bandwidth to increase with wavelength for an LCTF, both because of the passband increase plotted in Fig 2, and because of the increase of peak transmission seen in Fig 3. The measured increase in equivalent bandwidth with wavelength for a 5 nm wide filter is plotted in Fig 4.

d) <u>Rejection Ratio</u>



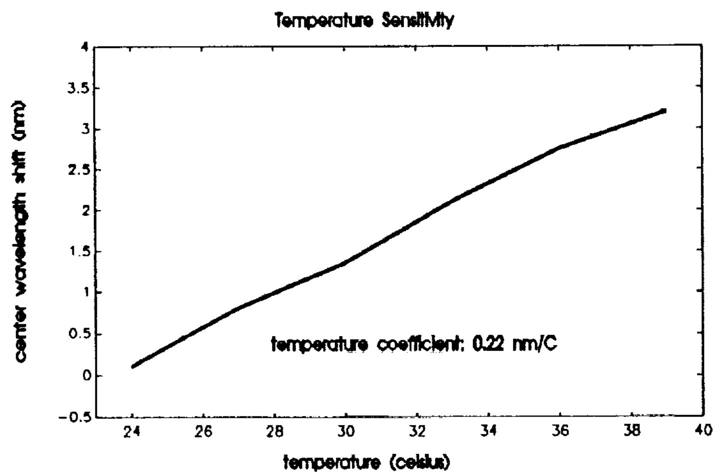
The measured out-of-band rejection of a typical ten-stage LCTF is shown in Fig 5, for a passband of 5 nm centered near 550 nm. The data show that out-of-band transmission is generally below 10^{-4}. This is below 10^{-3} of the peak transmission of about 15% at that wavelength.

e) <u>Center Wavelength of the Passband</u>

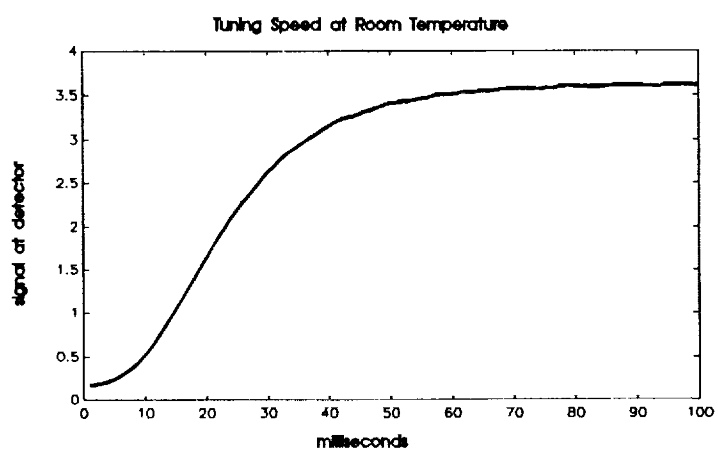


The off-axis shift of the center wavelength of the LCTF passband is shown in Fig 6. Modelling and tests on several filters of standard design show that the shift is less than 10% of the passband width for off-axis angles below 7%. Note that for birefringent filters this curve depends on the direction off-axis relative to the crystal axis; the particular curve plotted here at 45 degrees to the crystal axis yields the largest rate of shift with angle.

We have recently constructed an LCTF with wide-angle elements, whose off-axis performance is truly remarkable. This filter can be used at a half-angle of 25 degrees off normal incidence with the same shift of the passband as encountered in a 7 degree filter of normal design. Its performance is illustrated in section 7 below.



The temperature sensitivity of the center wavelength encountered in an uncompensated LCTF is shown in Fig 7. The correction provided by CRI's proprietary compensation scheme reduces this temperature sensitivity to a level enabling a 10-stage filter to operate between 18 C and 43 C with a passband drift below 0.5 nm.



The tuning speed of the center wavelength is illustrated in Fig 8, for performance at room temperature. The figure shows the change in signal as the passband shifts from an initial wavelength (of zero transmission, completely off a line source) to a final wavelength (at which the line source is passed). It can be seen that the time taken to achieve a signal level (i.e. passband position and shape) corresponding to 95% of the final signal, is typically about 50 msec. This value depends somewhat upon the initial and final wavelengths specified.

5. Comparison between LCTF's and Other Types of Monochromators Competitive with the Interference Filters Baselined for HEPI and ALM

Table 1 provides a comparative overview of several figures of merit for monochromators available for spectrally selective 2-D imaging on the HEPI and ALM experiments. The other types of filters (besides the LCTF) selected for comparison with the interference filters put forward in the baseline configurations for HEPI and ALM are: a) a piezo-electrically tunable Fabry-Perot etalon; and b) an acousto-optical filter (AOTF). Grating-based instruments were not included, since their spatial scanning does not appear compatible with the rapid exposure times required for ALM and for HEPI.

The parameter values we used in the comparison correspond to those available at the present time, without regard to cost, since the cost of this filter would be small relative to the overall cost of both the HEPI and ALM flight instruments.

The F.P. etalon is not well suited to either the HEPI or ALM, since its strength lies in the ability to achieve very narrow passband (< 1 Å), which is not required by either of these experiments. To achieve tuning over any appreciable spectral range, a F.P. would require a tunable prefilter, necessitating either a filter wheel, a LCTF or an AOTF, or perhaps several etalons in series.

The main strong points of interference filters mounted in a mechanical wheel are: a) high transmission, and b) availability of interference filters over the full HEPI wavelength range from 0.3μ to 2.5μ. The weak points are: a) mechanical moving parts; b) pixel mis-registration due to vibration; c) relatively high peak operating power requirement; d) slow wavelength changes; and e) limited and fixed wavelength choices.

AOTF's could operate over the full wavelength range required by HEPI and ALM. But they offer: a) relatively small aperture; b) low rejection ratio; c) high power consumption; d) RF noise generation; e) image shift; and f) relatively poor image quality. Their impressive tuning speed (μ secs) is of little importance in HEPI and ALM.

By comparison, the main advantages for ALM offered by the LCTF (over the filter wheel) is in its small size, low power requirement, and better reliability (no moving parts), but at the expense of lower peak transmission. The wide-angle design of the LCTF could enable ALM to obviate large-aperture filters placed before the optics, since a beam of approximately unity f-ratio could be accomodated. For HEPI, the LCTF offers the additional advantages of a) wavelength versatility and b) faster tuning time. Its drawbacks are again: a) lower transmission, and additionally; b) usable for imaging only at $\lambda > 0.4\mu$.

6) Space Hardening

A thorough study of the potential for space hardening of LCTF's was performed under a concurrent NASA contract NAS 7-1170. The results of that study are summarized in Table 2. The essential points are:

a) the glasses, CMOS components and electrical connectors used in the filter could be specified to pass space qualification testing, although this would not guarantee absence of degradation (e.g. radiation darkening of the glasses);

b) the Stycast and other epoxies presently used do not pass space qualification, but space qualified replacements can probably be found and/or the quantities used are small enough (e.g. the Stycast) that they would not prejudice space qualification of the filter;

c) the liquid crystals, polarizers and PVA need to be thermal vacuum tested to determine their space qualification properties.

d) Radiation damage data on LC and PVA indicate that damage caused by charged particles and hard photons may be a problem, but the conclusions are very dosage dependent. Further work using spectra and fluxes specific to geosynchronous orbits are required.

7) Conceptual Design of LCTF's for ALM and HEPI

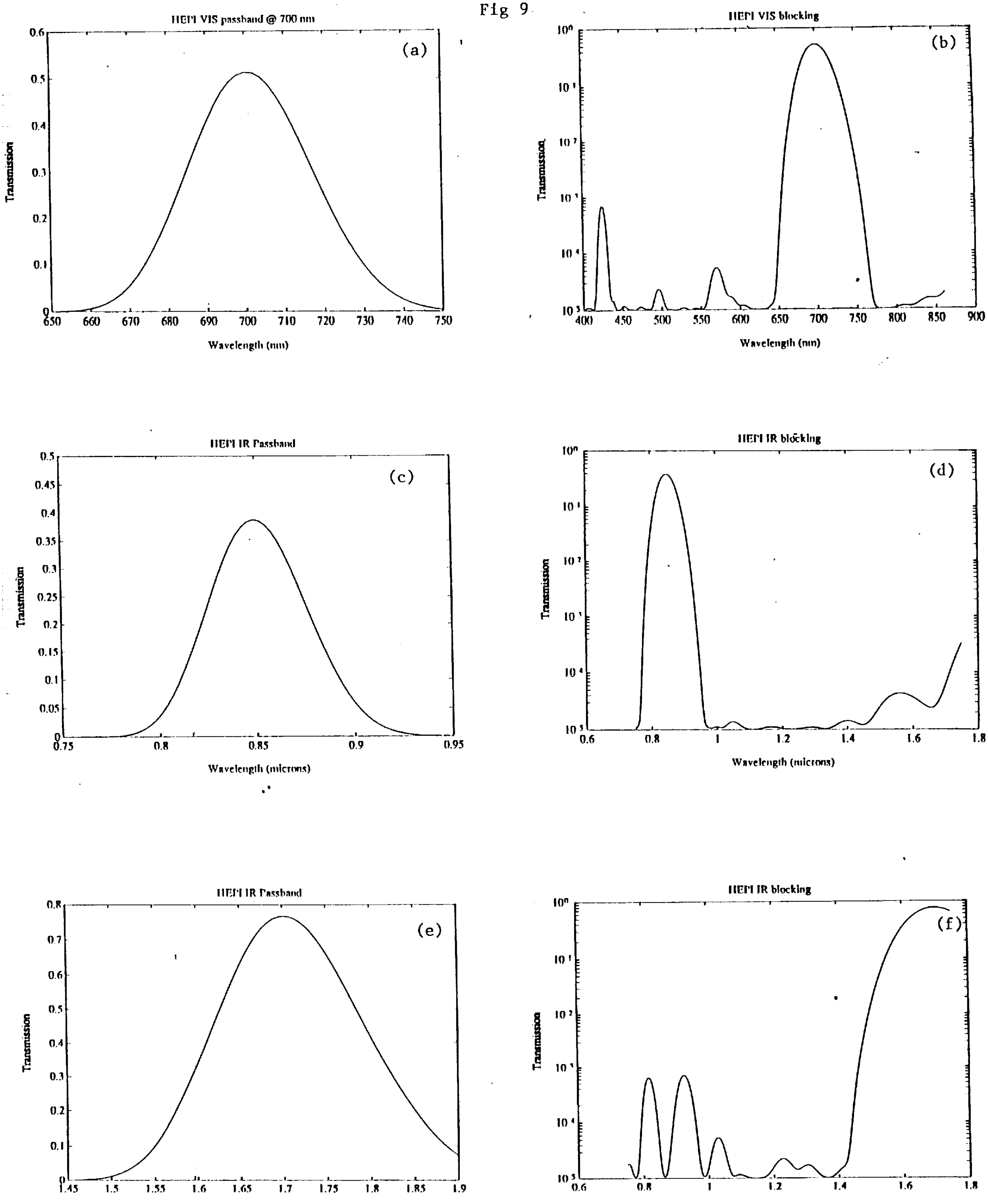
Based on the considerations discussed above we are able to put forward two conceptual designs for LCTF's optimized for use in the HEPI and ALM experiments. The filter design requirements are listed below.

a) HEPI
- i) λ-range: 0.3 (0.4) - 2.5μ
- ii) bandwidth: 20-50 nm for 0.48 < < 1.6μ
  200-300 nm for 1.7 < < 2.3μ
- iii) Acceptance angle: f 16
- iv) Aperture: 0.85 - 2.5μ = 2.1 cm
  0.4 - 0.9μ = 1.5 cm
- v) Transmission: as high as possible (compared to interference filter)
- vi) Rejection: 10^3
- vii) Tuning speed: seconds
- viii) Comments: input polarization must be compatible with feed off dichroic beam splitter

b) ALM
- i) λ-range: 0.5μ - 0.9μ
- ii) bandwidth: 6Å at 7774 Å
- iii) Acceptance angle: 5 degrees (if placed in front of optics)
- iv) Aperture: 2.5 cm
- v) Transmission: as good as possible (compared to I-filter)
- vi) Rejection: as high as possible (daytime lightning)
- vii) Tuning speed: > secs.

For HEPI, we modelled three designs whose passbands and blocking are shown in Figs 9(a-f). First, for the region between 450-875 nm, we modelled an 8-element filter whose passband of 35 nm FWHM at 700 nm is shown in panel(a). It can be tuned between 480 nm and 850 nm. The blocking properties of this filter between 450 and 875 nm are shown in panel (b), illustrated with the (tunable) passband located at 700 nm. The sideband below 450 nm could be

Fig 9

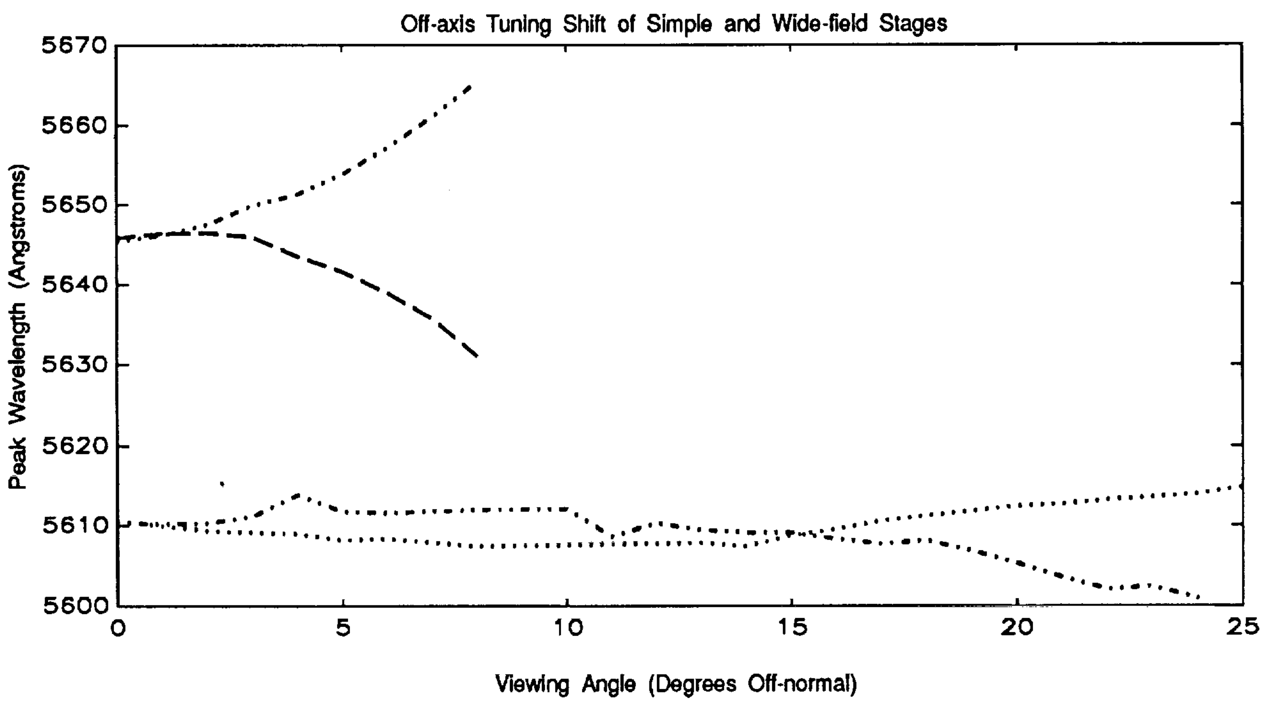


HEPI VIS passband @ 700 nm
(a)
Transmission
Wavelength (nm)
HEPI VIS blocking
(b)
Transmission
Wavelength (nm)
HEPI IR Passband
(c)
Transmission
Wavelength (microns)
HEPI IR blocking
(d)
Transmission
Wavelength (microns)
HEPI IR Passband
(e)
Transmission
Wavelength (microns)
HEPI IR blocking
(f)
Transmission
Wavelength (microns)

blocked with a glass filter, since the HEPI baseline document put forward by JPL shows no passband required between 310 nm and 480 nm.

For the HEPI IR filter, we modelled two designs - one set up to provide the filter of approximately 50 nm passband width specified by JPL at wavelengths below 1.7 µm. The other provides the 200 nm-wide passband specified above 1.7 µm. The passband and blocking of the narrower-band filter design are shown in panels (c) and (d) respectively. The passband center can be tuned between 850 and 1750 nm. The model results for the 200 nm IR filter are shown in panels (e) and (f).

For ALM, it is not possible to produce an LCTF of 6 Å passband tuning the full distance between 500 nm and 870 nm, as would be required to cover all the three sets of possible lines. However, we believe that the wide-angle LCTF design mentioned earlier in this report offers a more interesting possibility. The 25-degree acceptance half-angle of such a filter is compatible with operation in a very fast F1 beam, and with large off-axis viewing angles, encountered by a filter placed between the optics and detector of ALM (or LIS).



The performance of such a wide-angle filter stage is illustrated by the measurements on simple and wide-field stages shown in Fig. 10. The dot-dashed curves refer to behavior of the othogonal polarizations. The top two curves show the off-axis wavelength shift incurred by a simple stage. The bottom two show the much less sensitive behavior of the wide-field stage.

This location of the filter would obviate the large filter aperture necessitated by placement of the filter in front of the optics, as is done in the present LIS design. The tuning range available to a 6Å filter of this design would be limited to only about 50Å, so only the 7774Å lines would be accessible. But sufficient scanning would be available to compensate for imstrumental drifts and ensure optimum transmission. The main advantage is to avoid the need for the very large-aperture interference filter now required in the LIS and ALM designs.

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Harris, S.E., and Wallace, V.W., J. Opt. Soc. Am., 59, 6, 744-747 (1969).

Table 1

TYPE	RANGE [um]	B.W. [nm]	FOV * (1/2 <) [deg]	APER-TURE [mm]	T(peak)% **	REJECT-ION ***	THRU-PUT [Sr-mm2]	TUNE TECH.	TUNE TIME	OPTICS MODULE DIMENSIONS	OPTICS MODULE POWER
Liquid Crystal Tunable Filter (CRI)	0.34 - 5.0	0.1 - 25	7 (25)	22 dia. (100)	15	1 E-4	30 (700)	AC Drive Voltage	50 mSec	80 mm dia. 60 mm thick	300 - 600 mW
AOTF (Brimrose)	0.2 - 4.5	0.1 - 5	5	10 x 10 (20x20)	30	1 E-3	0.7 (3)	RF Drive Signal	~uSec	50 x 50 x 50 mm	20 Watts
Interference Filter Wheel (Barr/Schaeffer)	0.2 - 6	0.2 - 2000	8	50	10 - 80	1 E-4	100	Mech. Rotation	sec. (full rot.)	90 mm dia. 40 mm thick	~5 Watts (10 W peak)
FP/ Etalon Tunable Filter (Queensgate)	0.3 - 15	0.001 - 220	2	50	90	7 E-2 (F=150)	7	PZT	~5 mSec	240 mm dia. 90 mm thick	~1 Watt (scan rate depen -dent)

NOTE :

* FOV indicates off axis angle corresponding to a shift in passband center wavelength of 10% of passband width for the FPTF (assuming a 7 layer zinc sulfide/cryolit device with a 1.25 micron gap, center wavelength of 500 nm operating in order 5) and interference filter (assuming a filter with effective index of refraction of 1.7, center wavelength of 600 nm and bandwidth of 20 nm). For the AOTF, the FOV corresponds to the angle of incidence where the diffraction efficiency goes to

** T(peak)% indicates transmission for un-polarized incident light.

*** REJECTION indicates absolute transmission far from the pass band of the filter. This does not include sidelobes for the AOTF and multiple orders for the FPTF.

See comments on the various filters which follow for elaboration on the specifications given in the table above.

Table 2

Tunable Filter Space Qualification Matrix per MSFC-HBK-527

MATERIAL	QUALIFICATION STATUS	COMMENTS/REFERENCES
Stycast Emerson and Cummings 2850 FT (black)	FLAM : fails TV: passes with cure TOX: passes with cure	Since small quantities are used in the filter, it may still qualify for space flight by filing an MUA with MSFC Materials/Processes. (Sec. II.C, III.A.)
Glass (all glasses are essentially identical)	FLAM : passes TV: passes TOX: passes	Though glasses are accepted per the MSFC-HBK-527, they still suffer radiation darkening. Radiation blocking windows may be necessary. (Sec. II.D., III.A.)
Epoxy Master Bond, Inc. UV-15	TV: fails	A substitute can not be specified as yet. Any candidates must be tested in the filter application before citing them as a substitute. (Sec. III.B.)
Epoxy Expoxy Technology, Inc. 305	Test results for 301, 301-2: FLAM: fails @ 25.9% oxy. TV: fails TOX: passes	305 was not found in MSFC-HBK-527; 301 and 301-2 were found. 305 must be tested, or a suitable substitute found. A substitute can not be specified as yet. Any candidates must be tested in the filter application before citing them as a substitute. (Sec. III.B.)
Liquid crystal EM Industriers, Inc. Licristal ZLI-1132(TN) cyanobiphenyl	UNLISTED	The LC cell will have to undergo TV testing. Numerous articles have been found in the literature concerning radiation damage of LC materials. This may be a problem; impact on filter performance as yet unknown. (Sec. III.C., III.D., IV., VII.)
PVA Polysciences, Inc. 98 mol % hydrolyzed MW=25,000 cat. no. 04397	UNLISTED	Literature on effects on PVA due to ionizing radiation report crosslinking, oxidation and gelling even at low dosages; impact on filter performance as yet unknown. (Sec. V.)
Polarizer (PVA) Sanritsu Electric Co., LTD. cat. no. LC2-9518	UNLISTED	Same as above.
Hi-Gloss Black Epoxy Resin Ilnsl-X Products, Inc.	UNLISTED	Plan to omit from the filter construction. (Sec. III.C.)
Electrical connectors Precision Concepts, Inc. cat. no. S-25 360-468 phos. bronze, CDA# 521	UNLISTED	Plan to obtain space qualified connectors. (Sec. III.C.)
CMOS Components	N/A	National Semiconductor reports significant radiation damage to even MIL-M-38510(JAN) CMOS devices. They do make a radiation hardened line of components. (Sec. VIII.)

FLAM- flammability ; TV- thermal vacuum ; TOX- toxicity
References refer to the "Materials Space Qualification, June 4, 1992" text.