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Alternative 2

A SIMPLE INSTRUMENT FOR THE MEASUREMENT OF OCEAN COLOUR

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1. INTRODUCTION

The requirement for an inexpensive instrument for the measurement of underwater irradiance and radiance was discussed by the WOIRS Instrument Design Group. It was considered important to have a low cost design measuring at a number of discrete spectral bands in the visible region of the spectrum. An initial requirements specification and a component cost target of $5000 US were set at this meeting.

An alternative design approach is to use a spectrograph to form an image spectrum on a linear photodiode array, providing the advantages of measurement at a greater number of spectral bands with only a single optical input channel. However, compared to the discrete channel approach, the radiation transfer between the input optics and detector plane is less favourable due to losses in the spectrograph. In particular, typical active areas of commercially available linear photodiode arrays are in the range from 0.1 to 1.0 mm^2. Furthermore the numerical aperture of the spectrograph restricts the light throughput. Hence, greater signal gain is required between the detectors and data acquisition subsystem. Two diode array based designs were proposed at WOIRS as possible candidates for further investigation subject to the availability of funding.

This report describes a design based upon a grating spectrograph with a discrete linear photodiode array capable of being polled by an instrument controller providing measurement of 16 spectral bands. Section (2) summarizes the optical design of the spectrograph. An outline of the required electronics is given in section (3) and section (4) gives an estimation of optical losses and the available radiation at the detector plane.

2. INITIAL OPTICAL DESIGN (SOTON)

The design presented WOIRS was based upon a commercially available sixteen element linear discrete photodiode array. This array has detector elements with a 0.81 x 0.81 mm (0.66 mm^2) active area and a centre to centre pitch of 1.02 mm giving an overall array length of 16.14 mm. This array format is assumed for the calculations presented in this report although other choices of sixteen element discrete photodiode arrays with larger active areas are available.

The layout of a simple spectrograph design is shown in Fig. 1. It is comprised of two aplanatic achromatic doublet lenses and a linear reflective diffraction grating. The first lens collimates the diffuse light from the entrance slit. A high order rejection filter for the removal of radiation below 400 nm is included after the first lens. The filtered radiation is then incident upon a reflective, linear diffraction grating. The image spectrum of the light from the grating is then formed on the detector plane by the second lens.

The optical layout shown in Fig. 1 is for a spectrograph using the first order of diffraction from a grating with 600 grooves per mm. The collimating and decollimating lenses are off-the-shelf corrected doublets with a nominal focal length of 44 mm. It is possible to estimate the wavelength measurement bands for each of the photodiode detectors using the grating formula. The results of this calculation for the example layout are shown in Table 1 below. The non-linearity of the band central wavelength location should be noted. Locating the physical aperture stop for the spectrograph at the grating has the advantage of minimizing the size of grating required. It also makes the optical design symmetrical about the aperture stop leading to an automatic correction of odd aberration terms. For the design shown in Fig 1, the aperture stop mask should be designed such that the second lens operates at about F#4.5 to ensure that radiation at the edges of the spectrum is not vignetted by the lens clear aperture.

The doublet lens is well corrected for spherical aberration, chromatic aberration and coma. Freedom from distortion is obtained by using a symmetrical design about the aperture stop. The main uncorrected aberrations are field curvature and astigmatism. Initial raytracing studies of the doublet show that the effects of these are only significant at the edges of the spectrum when the detector array is placed at the optimum focus of the axial beam from the lens. This will affect the wavelength ranges in Table 1, resulting in a partial overlap in the wavelength bands at the extremes of the spectrum due to aberration blur. However, it might still be possible to produce a spectrograph design using off-the-shelf lenses by positioning field flattening negative singlet lenses adjacent to the entrance slit and detector plane such that correction of field curvature and astigmatism off axis is balanced against increased spherical and chromatic aberration on-axis. Such design considerations would need to be investigated during the next stage of instrument design.

Estimates of optical component costs for spectrograph construction are given below in pounds sterling:

2 x Achromat, aplanat doublet lenses @ £82.00 ea:	£ 164.00
1 x Schott GG395 filter for order selection:	£ 15.00
1 x 25 by 12.5 mm 600 l/mm diffraction grating:	£ 70.00
1 x Path folding mirror:	£ 100.00
TOTAL:	£ 349.00

Additional costs would be incurred for providing multilayer antireflection coatings for the components and in the construction of the spectrograph metalwork. However, based upon the above, it should be possible to construct such an optical system for a total **component** cost of around £1000. Further work on the likely costs of the optics would be carried out at the next stage of development.

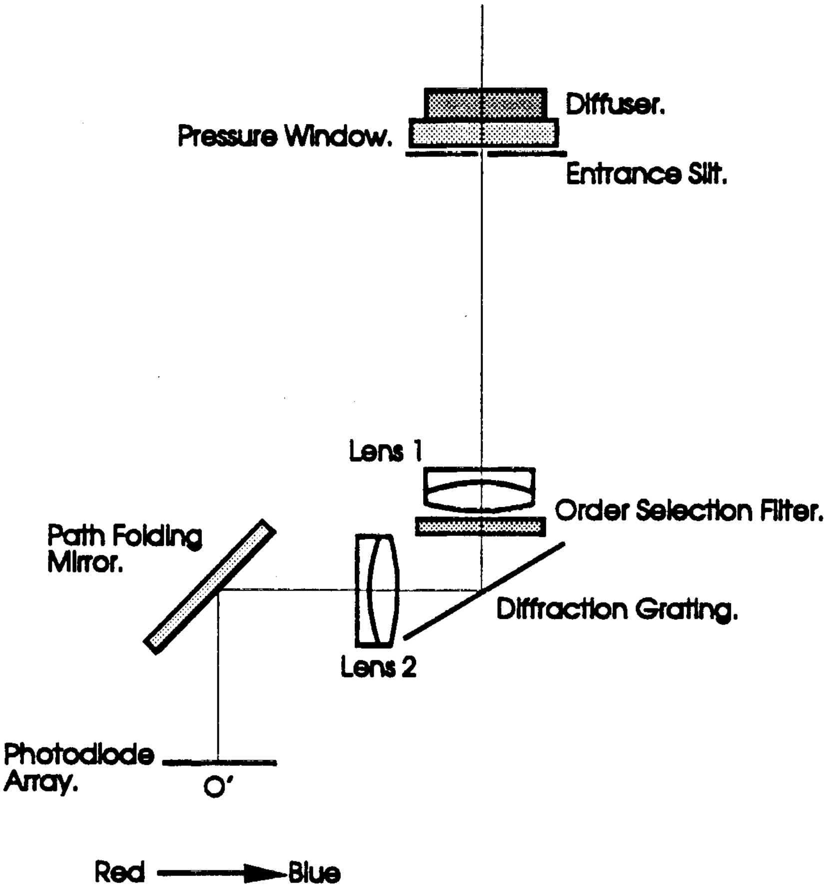
TABLE 1

Spectral Measurement Bands for Design Example.

For the linear photodiode array format of the initial optical design.

Element No.	Element X Position	Central Wave- length	Wavelength Range
1	-7.65	423.9	19.3
2	-6.63	447.9	18.9
3	-5.61	471.5	18.5
4	-4.59	494.5	18.0
5	-3.57	516.9	17.5
6	-2.55	538.6	17.0
7	-1.53	559.7	16.5
8	-0.51	580.1	15.9
9	0.51	599.7	15.3
10	1.53	618.5	14.6
11	2.55	636.5	14.0
12	3.57	653.7	13.3
13	4.59	670.0	12.6
14	5.61	685.5	11.9
15	6.63	700.0	11.2
16	7.65	713.7	10.5
[-]	[mm]	[nm]	[nm]

Fig. 1. Optical Layout for Spectrograph



Scale 1:1 Approx.

Lenses 1 and 2 : Aplanat, achromat doublets.
Order selection filter : Schott GG395, 2mm thick.
Diffraction Grating : 600 l/mm, reflective.
Photodiode Array : 16 element.

INITIAL ELECTRONICS DESIGN

A schematic of a possible implementation of the commutation and signal conditioning electronics for the instrument is shown in Fig. 2. The use of a sixteen element photodiode array results in a simple and hence inexpensive design. The first stage of amplification would be provided by four quad-package, low noise, jfet input transimpedence amplifiers. The outputs from these amplifiers are connected to a sixteen to one analogue multiplexer. The channel for measurement can then be selected by the instrument controller/logger. The output from the analogue switch is passed to a further amplification stage and is filtered to reduce noise before digitization in the controller/logger. The gain of the amplification stage after the multiplexer would be selected by the controller/logger with values of 1, 10, 100 and 1000. The value of the feedback resistance R on the detector transimpedence amplifiers would be selected to give a sufficient output level at the input to the controller at the lowest variable gain setting for the maximum expected input light level. An estimate of this value is given in the last section on the basis of a simple radiometric model of the instrument optics. Detailed design of the instrument electronics, taking the required dynamic range and sampling rate into account, will be deferred until the next stage of development.

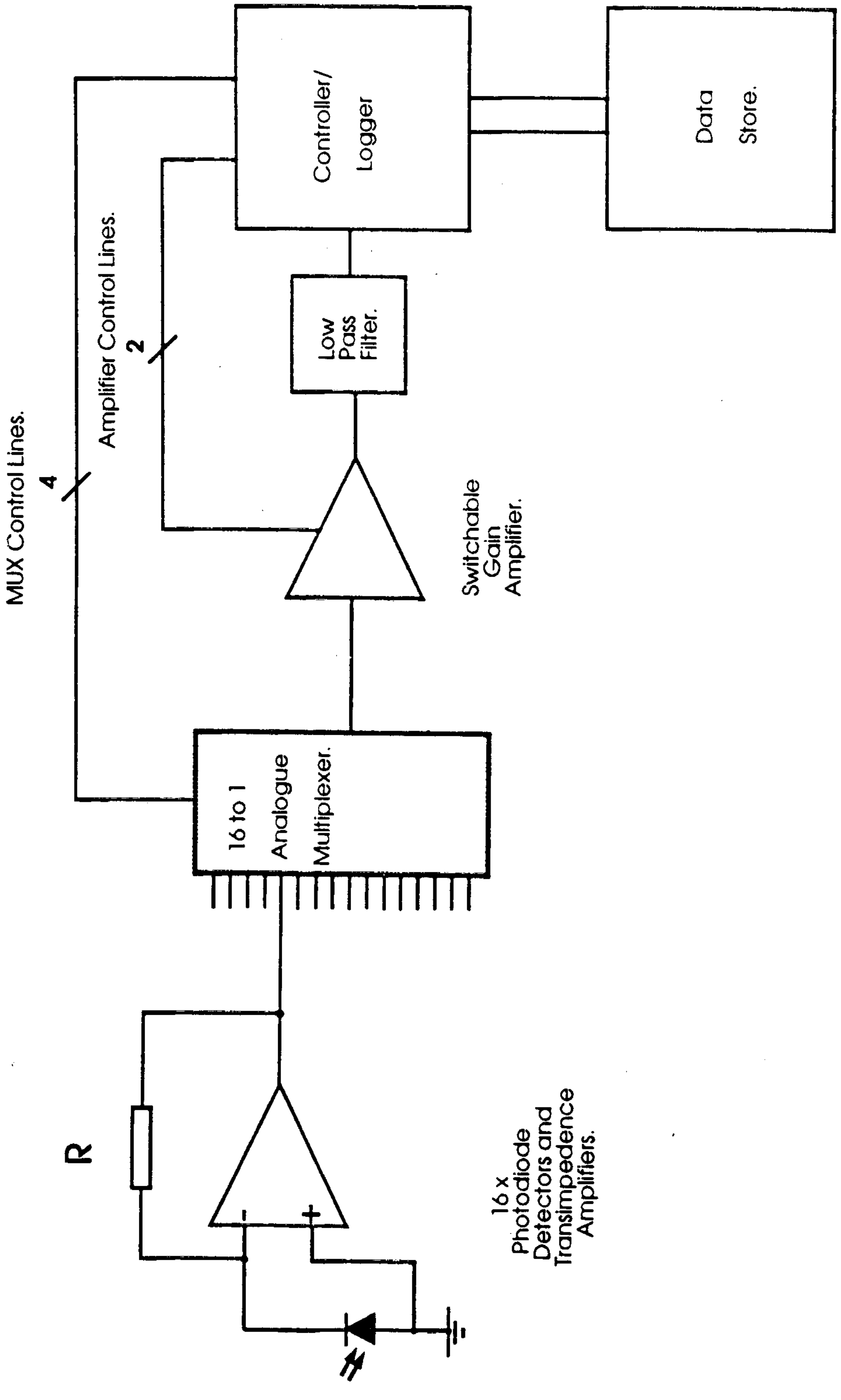
An estimate of the basic component costs is shown below.

Description	**Quantity**	**Cost**
Quad, JFET input op amps.	4	£ 60.00
16 Way Analogue Multiplexer.	1	£ 5.00
Switchable Gain Amplifier. (2 ICs).	1	£ 10.00
Low Pass Filter. (2 ICs).	1	£ 10.00
Controller/Logger.	1	£ 500.00
40 MB Hard Disk Module.	1	£ 300.00
TOTAL:		**£ 885.00**

Additional costs will be incurred for circuit board manufacture and for the power supply electronics. A non-recurring cost would be incurred in purchasing a development system for the controller/logger.

The prices quoted above for the controller/logger and data store are typical for small, low power, microprocessor based systems commonly used for oceanographic instrumentation. It is apparent that the costs of these items will constitute a high proportion of the overall component cost of the instrument.

Fig. 2. Initial Electronics Schematic



ESTIMATION OF OPTICAL LOSSES AND AVAILABLE RADIATION

The amount of radiation transmitted through the spectrograph from the diffuser to the detector plane can be estimated using the following equation:

$$E'' = T_1.T_2.(NA')^2.E \qquad (1)$$

Where E" is the irradiance at the detector plane,
E is the irradiance at the entrance to the diffuser,
T_1 is the irradiance transmittance of the diffuser,
T_2 is the transmittance of the spectrograph
and NA' is the numerical aperture of the image forming beam at the detector plane.

The spectrograph transmittance can be estimated using the following equation:

$$T_2 = (T_s)^n.(R)^m.G \qquad (2)$$

Where T_s is the transmittance per glass/air interface due to fresnel losses,
R is the reflectance per mirror surface,
n is the number of glass/air interfaces (including detector window),
m is the number of mirror surfaces (including the grating)
and G is the grating efficiency.

The grating efficiency is a function of wavelength. The locations of the peak efficiencies for s and p polarization planes separate on increasing the grating blaze angle. In general, the peak s-plane efficiency (light with E-field in a plane perpendicular to the grating grooves) remains at the wavelength at which specular reflection occurs from the grating facets while the p-plane efficiency peak moves towards shorter wavelengths [1]. If a 600 l/mm reflective diffraction grating with a Littrow blaze wavelength of 500 nm (blaze angle 8.63^o) is considered then the peak s-plane efficiency will occur at about 388 nm for the grating orientation in the spectrograph design. Then, the overall efficiency will roll off towards the red, partially compensating the roll off in silicon detector responsivity towards the blue. The grating efficiency will be taken as 1.0 and the detector responsivity as 0.2 A/W for the purposes of giving an initial estimation.

If the effects of aberration and diffraction on the instrument transfer function are neglected, then for the case when the entrance slit width is less than the detector width, the available flux for the formation of a photocurrent can be estimated by:

$$P = k.A_d.E''_\lambda.\Delta\lambda \qquad (3)$$

Where k is the ratio of the entrance slit image width to the detector width,
A_d is the active area of the detector element (m^2),
E''_λ is the spectral irradiance from equation (1) ($W/m^2/nm$)
and $\Delta\lambda$ is the wavelength bandwidth for the detector element from Table (1).

The values used in the estimation of the available flux based upon this simple model are tabulated below. The first column on the right of the first table gives the values substituted into the transmittance model (Equations (1) and (2). The last column gives te various contributions to the overall transmittance. The irradiance transfer (E"/E) is the product of the terms in this column. The second table gives the values used in the estimation of available flux using equation (3).

Diffuser irradiance transmittance T1	[-]	0.1
Air/Glass interface transmittance Ts	0.98	[-]
Number of air/glass interfaces n	9	0.83
Mirror surface reflectance R	0.92	[-]
Number of mirror surfaces m	2	0.85
Grating efficiency G	[-]	1.00
Image numerical aperture NA	0.11	0.012
Irradiance transfer (E"/E)	[-]	0.00085

Maximum spectral irradiance, E''_λ (WOIRS Specification).	4.0	$[W/m^2/nm]$
Irradiance transfer, (E"/E)	8.5e-4	[-]
Detector area, Ad	6.6e-7	$[m^2]$
Mean spectral bandwidth,$\Delta\lambda$ (From Table (1)).	16	[nm]
Instrument Factor, k.	0.1	[-]
Available flux, P.	3.6	[nW]

Taking a detector responsivity of 0.2 A/W, the available flux P will generate a photocurrent of about 0.72 nA. Hence a transimpedence resistance R of 1.4 GOhms (1.4e9 Ohms) would be required to give a signal of 1.0 volt at the output of the first amplification stage in figure (2).

5. CONCLUSIONS

On the basis of the initial design outlined in this report, a multi-band instrument based upon a discrete linear photodiode array is likely to meet both the WOIRS requirement specification and the component cost target. The combined component costs for the optical and electronics subsystems would be in the order of £2000 ($3000 US). This would leave a balance of $2000 US for the provision of additional components such sensors for temperature, depth and tilt monitoring and for encapsulation of the instrument for subsurface deployment.

It is suggested that the next phase of development should be to produce a detailed paper design before making any decision to proceed with the construction of a prototype instrument. This exercise will give a better idea of the likely costs and performance of the instrument. It will be executed subject to the availability of funding.

REFERENCES

LOEWEN, E.G., M. NEVIERE & D. MAYSTRE, 1977. Grating Efficiency Theory as it applies to Blazed and Holographic Gratings. APPLIED OPTICS V16: 2711-2722.