10 meter airborne observatory

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ABSTRACT

Inside an aircraft fuselage there is little room for the mass of all the instrumentation of a ground-based observatory much less a primary objective aperture at the scale of 10 meters. We have proposed a solution that uses a primary objective grating (POG) which matches the considerable length of the aircraft, approximately 10 meters, and conforms to aircraft aerodynamics. Light collected by the POG is diffracted at an angle of grazing exodus inside the aircraft where it is disambiguated by an optical train that fits within to the interior tunnel. Inside the aircraft, light is focused by a parabolic mirror onto a spectrograph slit. The design has a special benefit in that all objects in the field-of-view of the free spectral range of the POG can have their spectra taken as the aircraft changes orientation. We suggest flight planes that will improve integration times, angular resolution and spectral resolution to acquire targets of high stellar magnitudes or alternatively increase the number of sources acquired per flight at the cost of sensitivity.

Keywords: aircraft, airborne, primary, objective, grating, telescope

1. INTRODUCTION

Seeing and wave length gamut improve with altitude, and aircraft routinely fly tens of thousands of meters higher in the atmosphere than the most elevated terrestrial observatories. For this reason alone, aircraft provide a window on the heavens almost as useful as space-based observatories. Better yet, airborne observatories are based on the ground where they can be serviced. Nonetheless, no matter how thin the air at 15,000 meters where aircraft can operate, the turbulence against an aircraft with an open aperture port is enormous. Flying in the face of this obvious difficulty, NASA has attempted to modify a short fuselage version of the Boeing 747 to house a 2.5 meter telescope. Progress has been slow, and to date no observations have been made from the SOFIA aircraft despite outlays of hundreds of millions of dollars.

We have proposed an entirely new paradigm in primary objective design based on the use of very high resolution diffraction gratings and holograms. The potential exists to embed the primary objective of an astronomical telescope as an integral part of an aircraft fuselage without any opening to the atmosphere. The novel design enjoys an aerodynamic profile can match the shape of the original aircraft skin, sealing the interior from external turbulence while at the same time neutralizing air pressure that circulates over the fuselage.

1.1 High altitude telescopy

The earliest airborne observatories were based on balloon vehicles that could achieve altitudes of 30,000 meters, but they were operated remotely and had relatively short one-time flights. Chasing a balloon observatory during its flight is like chasing a tornado with ground vehicles racing to meet the gondola as it returns to earth. The launch and rescue of the balloon occupies a major part of the operation, and there have never been routine nightly observations made from such unwieldy platforms.

The backbone of astronomical observation is situated on mountain peaks. There are a few select mountain ranges and extinct volcanoes where the proper infrastructure has been raised to service billions of dollars of optical instrumentation carried up twisting mountain roads and installed in forbidding cold, wind, and rock. Nightly observations are possible from mountain tops, weather permitting, but at 3,000 to 5,000 meters, these peaks are not so high as to assure that clouds and atmospheric turbulence will not interfere with seeing. Moreover, deep infrared and terahertz bands are not present due to water vapor absorption. Only the redundancy of many observatories provides some assurance that one-time events will be captured. Even with good weather, a one time-event with priority can bump the scheduled observations. For a scientist with only one observation block scheduled, bad weather or a priority bump can kill years of advanced planning.

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1.2 Aircraft

While radar dishes fit nicely in the nose cone of an aircraft, optical mirrors do not work when similarly shrouded. This is especially true for diffraction limited mirrors which would be degraded by a transparent nose or tail cone. Moreover, the nose or tail of an aircraft does not routinely point toward the sky, making a flight path for observation improbable or even impossible without a folding mirror. Moreover, some wavelengths of interest are attenuated by glass. The alternative is to open the side of the aircraft to the air and view upwards. This approach is the basis of the SOFIA experiment[1] which is in a modified wide body aircraft, Figure 1.

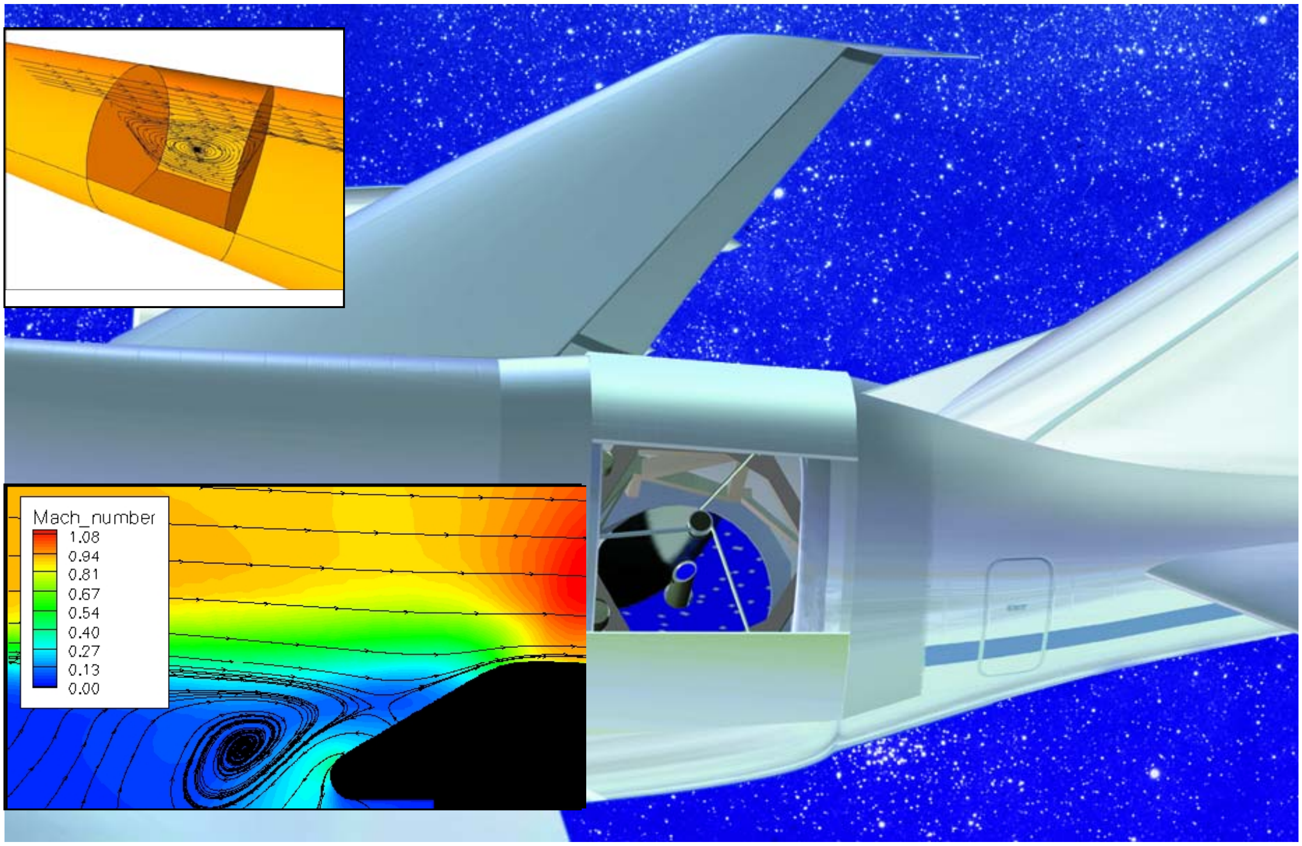

Fig. 1. Stratospheric Observatory for Infrared Astronomy, SOFIA, will be carried aloft in a side-looking Boeing 747-SP. Inserts show predicted vortices from open cavity (top) and wind shear control using curved lip as an air foil (below).[2]

Modification of the aircraft required extensive reinforcement of the tail section framework, since the structural integrity of a fuselage derives from symmetrical load distribution. With SOFIA, the opening creates turbulence and diminishes strength at the very site where the turbulence occurs. The concept passed a critical worthiness test based on wind tunnel assessments in 1997, but resonant frequencies must be extrapolated from these scale models. The open cavity is similar to a flute embouchure in that fixed frequency acoustical waves will continuously resonant inside the well. It is predicted that for this opening the periods will be on the order of 40 Hz, and there will be at least two such low frequency acoustical pressure waves. No one really knows yet if the gimbaled telescope platform will successfully counteract the pressure. The goal is to achieve sub-arc second stability. A flight with the telescope cavity door opened is scheduled for late 2008. Observations may begin in 2009. It was once hoped that flights would begin eight years earlier.

2. PRIMARY OBJECTIVE GRATING AT GRAZING EXODUS

A primary objective grating (POG) exhibits a magnification feature when flux is collected off-axis. The effect is much like a lever, the longer the POG, the greater the magnification. The entire length of an aircraft fuselage can be exploited as the optical surface for a telescope if it constructed from grating segments that run along its skin surface. Fuselages with available 10 m surfaces provide a platform that can operate at 15,000 m or higher in certain types of aircraft.

2.1 POG telescope concept

A diffraction grating of groove pitch *p* forms an image by wavefront reconstruction at angles *r*. Peaks of constructive interference occur at discrete nodes, denoted as the integer diffraction orders *n*. A wavelength λ is concentrated for collection by a secondary at each node. By a novel use of double dispersion we have exploited this phenomenon because we account for the coincidence of all nodes in the free spectral range for discrete sources that vary over their angles of incidence *i*. The controlling relationship is the diffraction equation which stipulates that

$$\lambda = \frac{(\sin(i) + \sin(r))}{n} p \tag{1}$$

When *r* is fixed and at an angle approaching grazing exodus near the grating surface, and when groove pitch *p* is equal to the wave length at the center of the free spectral range, then in the first-order *n* = 1 the arc of *i* can be seen over angles spanning 40°. For example, in the visible spectrum if p = 600 nm and the angle of grazing exodus *r* is 85° then the free spectral range is 400 nm to 800 nm and the field-of-view (FoV) is 38.943°.

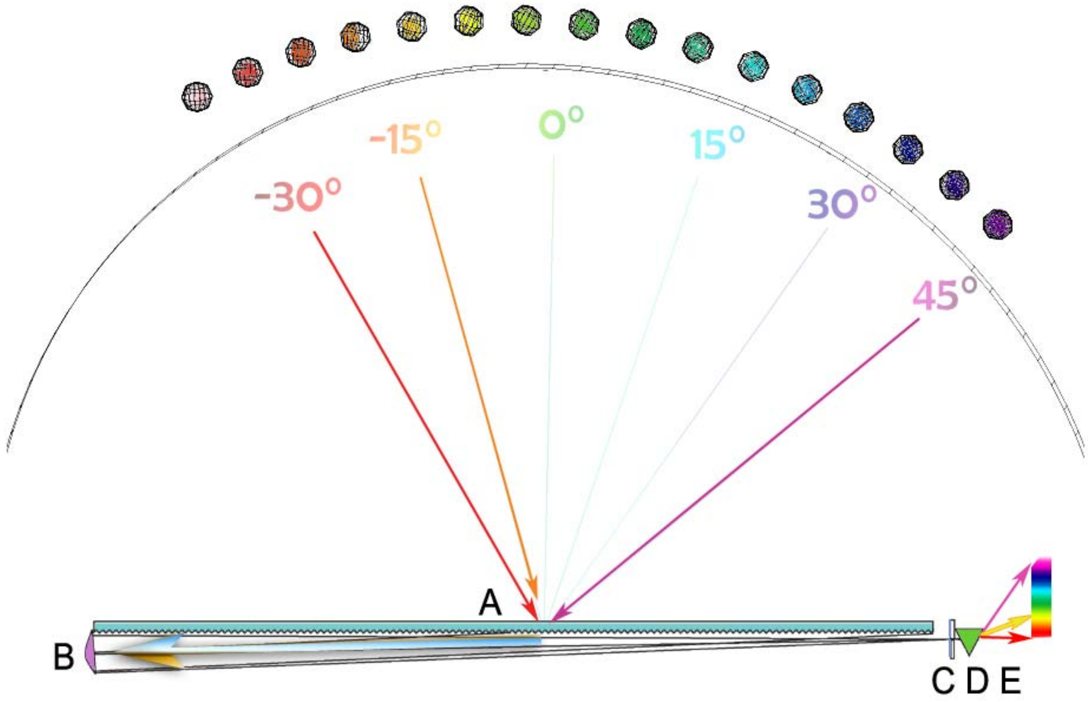

Fig. 2 POG **A** redirects light to secondary parabolic mirror **B** that focuses light on slit **C** of spectrograph **CDE**.

Figure 2 is a diagram of our POG astronomical telescope. The POG **A** is shown in transmission mode, but Equation (1) applies equally to both transmission and reflection diffraction gratings. The ratio of the length of the POG to its secondary mirror **B** is the magnification power of the primary. The power grows with the angle of grazing exodus. Incident angles are selected by wavelength to be displayed as a spectrogram In order for the spectra of superimposed sources to be disambiguated, there must be a secondary spectrograph **CDE**. For any source there exists an instantaneous wavelength band determined by the width of slit **C**. The instrument would not take complete spectra if the sources did not precess. However, precession of sources by the rotation of the earth and the flight path of an airborne observatory provides the progression of angles of incidence needed to produce all wavelengths of all sources as a function of time.

2.2 Data reduction

Data reduction from the sequence of spectrograms is a process of sorting through snapshots taken over the course of an observation cycle. The process can be understood by thinking of a spectrum that is in transit and is superimposed over the heavens, Figure 3.

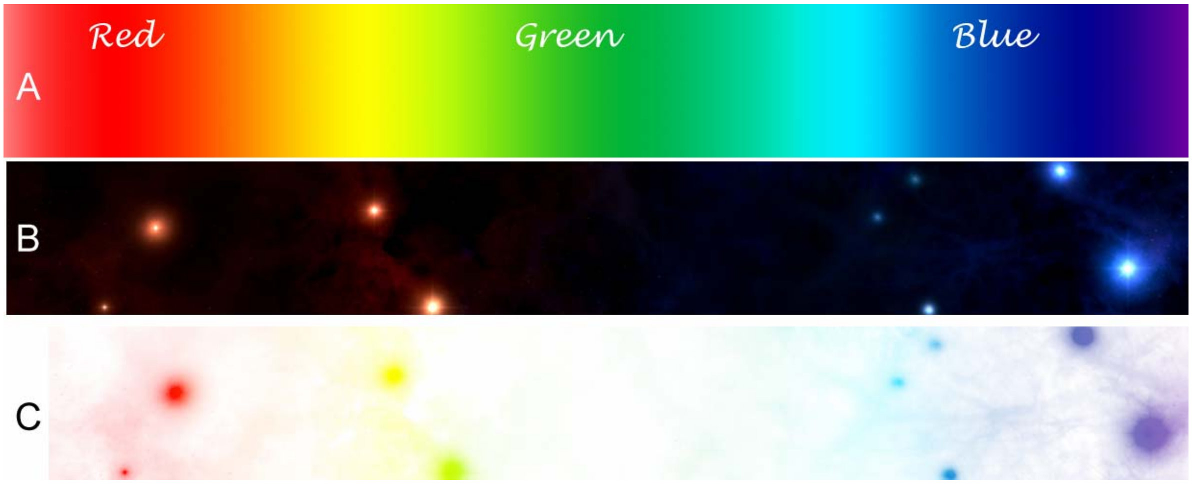

Fig. 3 Spectrum **A** superimposed over sources in strip **B** produces hyper-spectral image **C**.

At any instant a wavelength band associated with a source can be measured for its amplitude. As the spectrum which is superimposed over the stars shifts, the sequence can reveal all amplitudes for all bands of all sources, Figure 4. A line across the considerable width of the three frames on the left of Figure 4 is reproduced as the instantaneous amplitudes of all objects in three spectrograms on the right. One source is drawn out for study by the vertical line that forms a cross on the target object. It is identified within the spectrogram on the right by a circle. As it precesses the history of its amplitudes at all bands can be recorded.

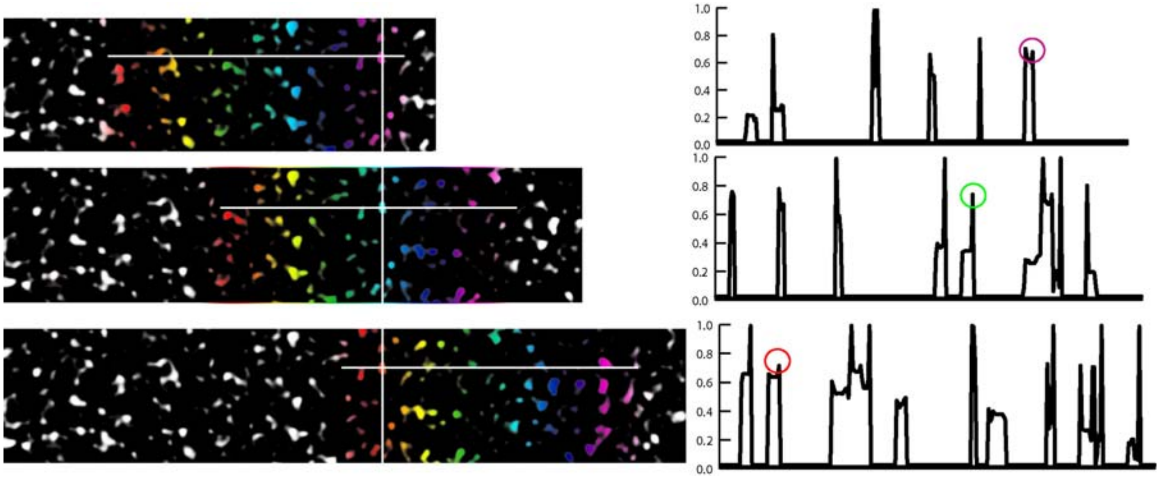

Fig. 4 Three sample frames in the course of an observation. The circles of the spectrogram on the right correspond to one source marked by crosshairs on the left.

The POG method exploits the magnification of spectra afforded by the use of a dispersive primary, and the result is that all spectra of all objects are being recorded all the time. The number of objects is potentially in the millions per observation cycle with each object being recorded to resolving powers of six figures or better. The use of computers makes the recording tenable. Sidereal time and the flight angle of the aircraft give a fix on each data point in the sky. When the position of a data point is known, its amplitude at each recorded wavelength can be stored in a table. At the completion of the observation, a spectrogram will appear at every point. Many points will be dark, as would be expected, and some points will be contaminated by overlaps with proximate objects, but all data will be spectrographic.

3. DEMONSTRATION

3.1 Bench top

The principle of the POG telescope has been demonstrated at miniature scale using a 5 cm holographic plane grating as the primary objective. The secondary was assembled from a camera lens as the collimator and an Ocean Optics fiber fed USB-4000 miniature spectrometer. The “stars” were incandescent tungsten sources placed a few meters from the POG. The bench top is shown in Figure 5.

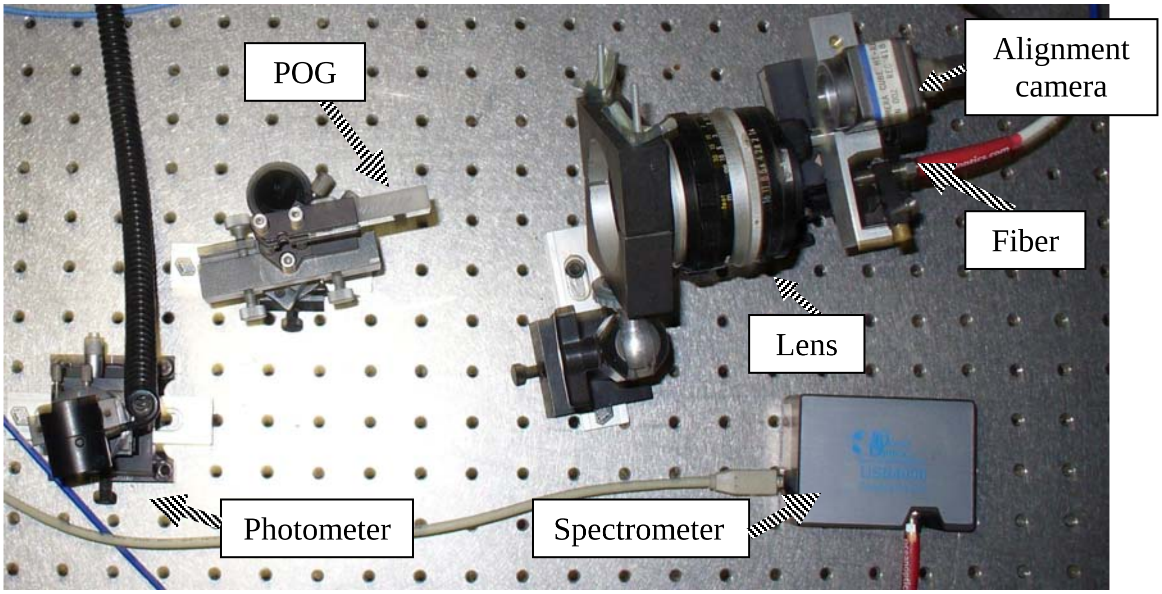

Fig. 5 50 mm POG with secondary made from camera lens and fiber fed spectrometer. Photometer read overall incident flux

In Figure 6 we see sources at 33.3 meters distance, a tractor with its head lights on. Wavelengths recorded by the spectrometer correlate to angles of incidence on the POG. Taken during the day to demonstrate how the aerial POG can be used for terrestrial resource management and again at night to demonstrate its use in astronomy, we see a spike associated with the tungsten filament of one inline head lamp. A second lamp, slightly off the lateral axis is diminished in intensity; shows that lateral sources are segregated.

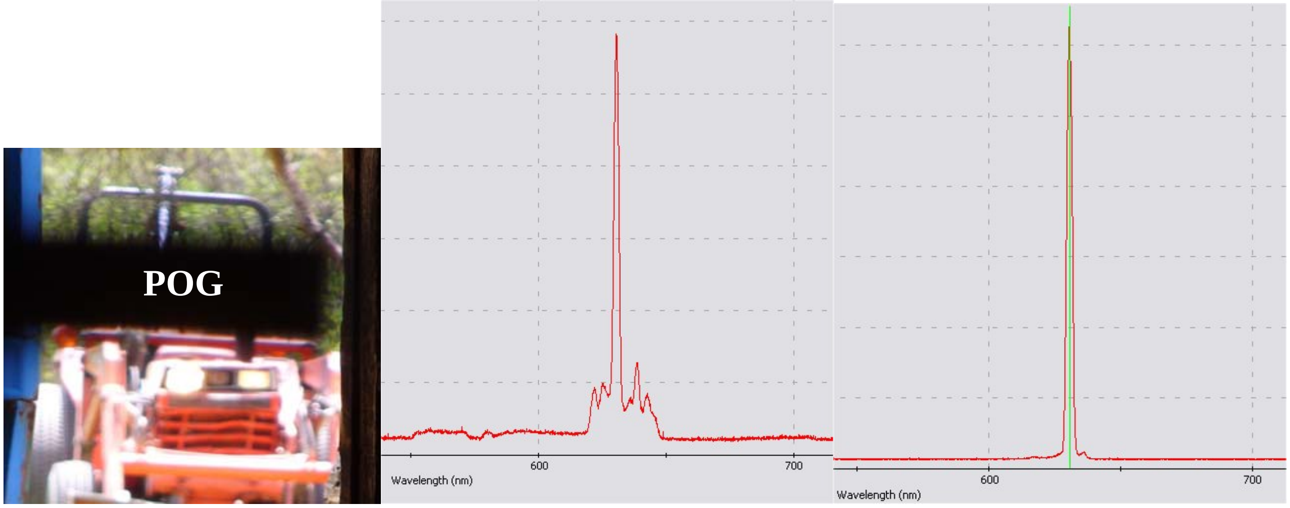

Fig. 6 Orange tractor with two headlights taken with POG and secondary spectrometer. Left: a view of the tractor. Shadow of POG in the foreground. The middle spectrogram shows a daytime recording. Spectrogram on right taken at night; one headlight directly on axis vastly outshines the other showing that the POG distinguished the vertical dimension.

3.2 Zemax model

We have POG telescope models realized in Zemax that look at reflection and transmission plane grating primaries. The POG can be scaled to sizes suitable for different applications.

Figure 7 shows the telescope with a reflection POG where the ratio of the POG length to the secondary mirror is 25:1. The spectrograph is also laid out in a grazing configuration and is half the length of the POG above it. The goal is to reach a resolving power commensurate with the primary objective, since this will determine both angular and spectral resolving power.

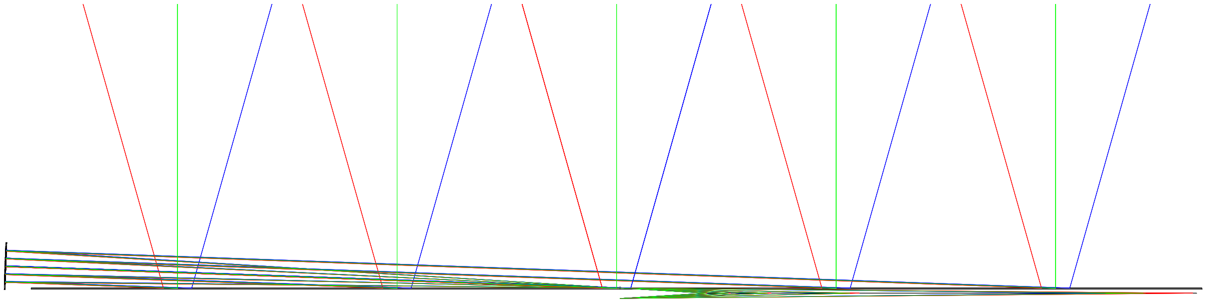

Fig. 7 Zemax model of reflection POG with a 30° incident FoV over the visible spectrum. Spectrograph is a long grating parallel to the POG and below it forming an image at a focal plane array in the center.

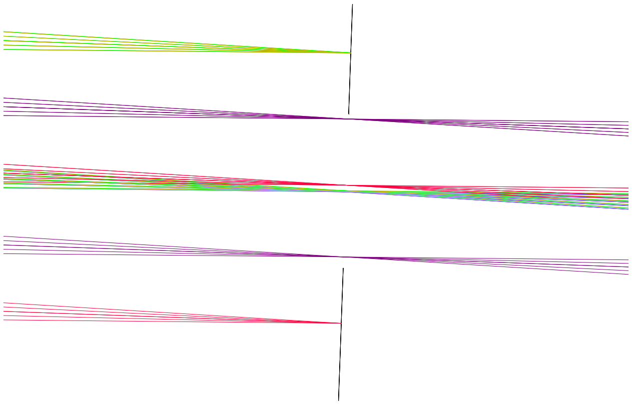

Fig. 8 Zemax model of 300 μm slit after 10 m POG

A slit for the secondary spectrograph, Fig. 8, is positioned in the POG at its midpoint. For a ten meter POG, the slit would be less than 500 μm. The rays occluded by the slit are off-axis by both wavelength and angle of arc. At 550 nm, the wavelength can be resolved to 0.005 Å over an angular resolution is 0.36 arc seconds. Increases in bandwidth are proportional to slit width with a corresponding decrease in angular resolution.

While a slit open to the sky would probably require depressurization of the payload bay housing the telescope, the narrow slit presents virtually no turbulence penalty for direct access to the atmosphere without a window. Given the superior performance of a spectrograph in a vacuum, the loss of pressure in the payload bay of the aircraft is probably to its advantage.

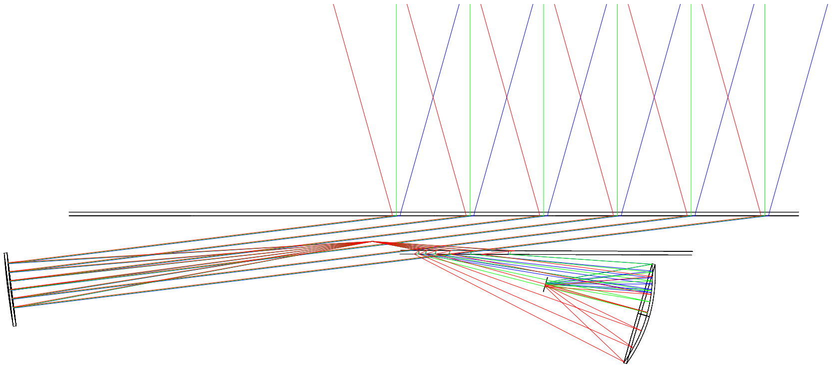

Fig. 9 Transmission POG with secondary mirror on left and spectrograph on right. A folding mirror serves as a slit.

A transmission grating was modeled in Zemax for use in the visible spectrum, Figure 9. It has the advantage that the cabin would be sealed and could be operated with air pressure maintained. A transmission POG would involve a relatively straight forward aircraft modification, Figure 10. The POG segments readily, so the modification is structurally equivalent to putting windows on the roof. The secondary mirror and spectrograph would be housed inside. Operator access would be possible during flight..

Fig. 10 A concept sketch of the exterior of a transmission POG aircraft. POG segments are placed like windows on the roof.

Reflection gratings would require a special aerodynamic roof pod to house the secondary mirror. The POG can be laid out as a continuous strip, since the only penetration into the fuselage is a very narrow slit at the secondary mirror focus. That slit will cost cabin pressure, and the optics might be remotely operated depressurized from behind a cabin bulkhead.
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4. FLIGHT PATHS

The use of an aircraft as the platform gives the POG telescope increased flexibility in controlling its integration time. This compares with fixed terrestrial settings where the integration time is inexorably linked to the rate of rotation of the earth. Presuming that the aircraft can be put through a slowly changing and sustained arc, the dwell time on targets can be improved by flying east to west in a convex path or west to east in a concave path. The inverse flight path will effectively increase the FoV over the equivalent period for a terrestrial version of the POG. See Figure 11.

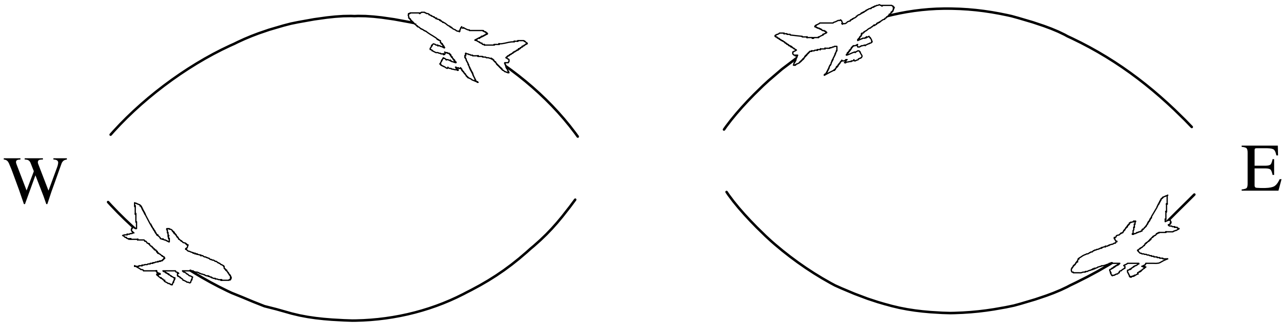

Fig. 11 Increased integration time by flight path on the left compared with increased survey data with flight path on right.

Rotational banking can be used to counteract the latitudinal arc that naturally occurs if a terrestrial POG is pointed north or south off the Great Circle.

5. CONCLUSION

We propose a new type of astronomical telescope that overcomes structural challenges faced by airborne parabolic reflection primary objective telescopes carried aloft. We have demonstrated the principle of operation on the bench and modeled large instruments in Zemax. In terms of the airframe, the POG telescope can be completely enclosed inside the fuselage, allowing the payload to be attended by its crew under normal cabin pressure. Alternatively, the payload area may be open to the high altitude atmosphere through a hair-wide slit that presents little aerodynamic turbulence. In the latter setting, the ray path can employ entirely reflective surfaces, and the receiver can work in deep infra-red or violet bands not available to terrestrial observatories due to atmospheric absorption. Modifications to existing aircraft involve installing windows on the roof or externally mounting reflection surfaces in aerodynamic pods.

One of the limitations of terrestrial POG installations is the inexorable rate of rotation of the earth which restricts integration time of an instrument that is already light starved. The airborne platform offers a means to extend the integration time. For low magnitude objects, the flight plan can be designed to increase the FoV, increasing survey yield. As a consequence of the unique features of the proposed telescope, all data will be entirely spectrographic. If an object is observed, it will be acquired with a spectrum. These and other features discussed elsewhere[3-6] make the POG an interesting innovation suitable for future study.

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