Schmidt Trim Plate Overcooling

Roger Smith, 2005-12-09

A plausible cause of seeing degradation on the Schmidt is the radiative cooling of the forward baffle and corrector, which must surely produce a pool of cold air that will be trapped by the baffle currently extending in front of the corrector. This might be mitigated in the classical configuration of the telescope by redesigning the baffle to allow cold air to slide sideways and sink below the beam, but in ZTF the placement of the shutter in front of the corrector creates a well, which if passively vented in this way would result in a substantial light leak.

Venting of the air in front of the corrector does not address the inverse convection (falling cold air) on the inner surface of the doublet that will create tube seeing.

# How much will the Trim plate cool?

The discussion in Appendix A (picked from a physics blog on the web) indicates that effective sky temperature can plausibly range from 4 C below ambient on a mild evening (15 C) with moderate humidity, to 16 C below ambient on a cold night (5 C) in the desert (5% night time relative humidity). We could experience these conditions on Palomar.

Overcooling of the baffle by radiation to the sky will tend to drain cold air into the area in front of the corrector.

Convection is not occurring above the corrector since the cool area will remain stratified and cannot drain away.

Conduction in still air is negligible compared to radiation.

Lateral conduction in the glass is poor due to the high aspect ratio and low thermal conductance of the material.

The temperature will be dominated by radiative equilibrium. For the corrector alone (all temperatures in Kelvin):

 2Tcorr4 = Tatm4 + Ttel4

Let’s assume the telescope temperature, Ttel, is at ambient and Tatm is the equivalenttemperature of the atmosphere to be used in radiativetransfer equations as described in the appendix.

For Ttel = 5 C = 278 K and humidity is 5%, equivalent temperature of the atmosphere, Tatm = -11C = 262 K, then Tcorrector = 270 K = -3 C. i.e. 8 K below ambient.

Placing the trim plate in front of the doublet moves the doublet temperature closer to that of the telescope tube. This has the positive effect of reducing tube seeing due to inverse convection, but does not eliminate it. However the trim plate temperature is lower than the doublet alone, increasing the risk of seeing due to cold air pooling above the trim plate.

Solving the Stephan-Boltzman equations for four plane parallel surfaces, one estimates the corrector temperature to be:

 3Tcorr4 = 2Ttel4 +Tatm4

So Tcorr = 273 K = 5K below ambient

and the trim plate temperature is

 3Ttrim4 = 2Tatm4 +Ttel4

So Ttrim = 267.7 K = 10.3K below ambient

# How much does convection reduce this effect?

I offer only a an order of magnitude estimate to show heating by convection will be a minor effect. Convection can be neglected for the trim plate which sits in a well below the shutter so inverse convection is not operative on the top surface. The bottom surface has no path for the air to escape. There will however be some inverse convection from the bottom surface of the doublet which could be as much as 5K below ambient.

Heat capacity of air (constant pressure, @295K) = 1.00 kJ/kg/K = 1.00 J/g/K

Density (295K, 2000m) = ~1.0 kg/m^3  = 1 g/liter (how convenient)

So heat capacity = 1 J/K per liter

Let’s be generous and allow that air temperature fully equilibrates to the temperature of the doublet before falling away.  Maximum dT = 5 K so the air flow required per watt of heating = 0.2 liter/sec

To completely warm the doublet by air flow would requires 274/2 W (for pi steradian visibility to sky on a dry night) thus 27 liters/sec if dT=5K.  My guess is that would be lucky to see 5-liters/sec falling from the bottom surface of the doublet and thus convection is at best a 20% effect - probably less and only on the doublet.

# How quickly will trim plate cool ?

Assuming

thickness = 9 mm

density = 2210 kg/m3 (assume like fused silica)

specific heat = 713 J/K/kg

thus

 heat capacity for 1 square meter = 14.2 kJ/K

so for radiative cooling at ~120 W/m2, *initial* slew rate is

 dT/dt =120/14200 K/s = 0.5 K/min

After 10-20 minutes exposure, the corrector will come close to equilibrium temperature with sky.

# Do we get condensation on the corrector?

This is not as easy to answer as one might expect. Condensation on the corrector will increase scattered light but moderate condensation may not be readily apparent in images. We know that this by analogy to observing with a dirty corrector or primary, as is common practice. So, it is not clear that condensation would be noticed.

The equivalent temperature of the night sky is lowest when humidity is low so it is possible that the corrector can often cool well below ambient without going below the dew point.

However we recently discovered that south edge of the original corrector cell has rusted to a depth of ~2 mm along the south edge that faces downwards when the telescope is parked. The new cell for the doublet, which was installed only 15 years ago is well on its way to the same condition.

<Jeff Zolkower will provide photos>

The amount of rust seems to be too high to be caused by the washing of the corrector since this is not done often and care is taken to mop up excess water. It is more plausible that the rust is caused when condensation accumulates at the lower edge after the telescope is parked at the south access location.

# What is the scale of the negative effect on seeing?

For reference, we have seen tube-seeing effects in extra focal imaging movies at >5 C deltas, but this was for warm surfaces that promote convection.

Inverse convection from the corrector remains a concern when humidity is low and corrector temperature drops ~5 K below ambient.

The trim plate and baffle will eventually fill the area enclosed by the baffle in still conditions. To get a sense of the image motion occurring when this air sloshes around, let’s approximate it as an isothermal wedge. Assume all air in the wedge is at the trim plate temperature and all air outside the wedge is not. The angle of the horizontal surface of the air wedge with respect to the corrector surface is the angle of the telescope to zenith, α.

 η-1 = 272 ppm at 633 nm and STP.

So the fractional change in one minus refractive index is 272ppm (Ttel-Ttrim)/ Ttel .

Thus the beam deviation at the pupil (image motion at the focal plane) produced by this wedge of cold air is

 Image motion = arctan( tan(α) \* 272ppm \* (Ttel-Ttrim)/ Ttel )

For Ttel = 278 K and Ttrim = 267.7 K as in the example above:

at α =60 degree zenith angle, image motion = 3.6 arcsec

 at α =30 degree zenith angle, image motion = 1.2 arcsec

This seems both plausible and significant. In reality, the air above the trim plate will be a moving and contain temperature gradients. The integrated effect may several to 10 times less as a result, but the depth of the air pocket could also be greater than modeled, bringing the number back up again.

# What can we do about it?

1. Warm the forward baffle to ambient with an electrical heater, so that trim plate radiates into smaller solid angle, and so the baffle does not shed cold air onto the trim plate. (Baffle needs to be somewhat conductive if temperature controlled.)
2. Heat the interior of the trim plate by running a current through an ITO coating as we are doing for the dewar window. A 1-2% throughput loss in the ITO is estimated by a prospective coating vendor. It doesn't take much image quality improvement enough to outweigh this penalty.
3. Create opening at the base of the baffle so only the depth of the shutter and space behind it trap air as opposed to the entire baffle depth. (This may not be required if the measures above are invoked.)

# How much power is radiated to sky by the trim plate?

The exposed area of the trim plate is 1.2 m2. The examples in the appendix quote 198 W/m2 to 274 W/m2 (for flat surfaces having unit emissivity). If we provide make up heat to the *baffle* in front of the shutter then solid angle is reduced and these numbers can probably be halved.

To hold the trim plate at ambient temperature we thus need about 120 W to 170 W to be dissipated in the ITO coating.

# What voltage would be required across an ITO coating ?

To achieve uniform power density, the circular shape requires voltage to vary along the perimeter. In practice we would provide multiple contacts each wired to different voltages to make a step-wise approximation. 4 different voltages and seven contacts per side is probably fine enough quantization.

Assume the required power density is uniformly ~ 120 W/m2. An ITO coating delivering only 1-2% throughput loss is predicted to have 500 ohm/sq sheet resistance. Voltage drop per meter = sqrt(120\*500) = 244 V. The peak voltage, 320 V will occur across the contacts spanning the full diameter of the trim plate. This voltage is high but not unreasonable to generate with a simple step up transformer and will be hidden out of reach so electrocution risk is eliminated. Voltage can be automatically shut down when the shutter is closed.

# Appendix A

The Swinbank formula provides an *ad hoc* expression for the power radiated by the night sky. A modified version of this formula from Goforth et al. is

*P* thermal =(1+*KC*2) 8.78×10−13 *T* 5.852 *RH* 0.07195

where

* *K*  is a scale factor based on cloud height, ranging from 0.34 for very low clouds to 0.06 for very high clouds,
* *C*  is the fraction of the sky covered by clouds,
* *T*  is the surface temperature, in kelvins,
* *RH*  is the surface relative humidity, as a percentage (e.g., *RH*  would be 25 in the case of 25% relative humidity), and
* *P* thermal   is the night sky radiation, in watts per square meter.

This can be converted to an effective temperature via the Stefan-Boltzmann law. Now the question arises as to whether one is asking about the effective black body temperature or effective gray body temperature of the night sky. In the first case the Stefan-Boltzmann law yields

*T*=(*P*/*σ*)1/4

Taking emissivity into account yields

*T*=(*P*/(*ϵσ*))1/4

where *ϵ*≈0.74 is the emissivity of the atmosphere.

A couple of examples:

* A cool clear night in the desert, with a temperature of 5°C and a relative humidity of 5%. The modified Swinbank formula yields a flux of 198 w/m2, which in turn corresponds to a black body temperature of -29.9°C or a gray body temperature of -10.9°C.
* A warm clear night in the countryside, with a temperature of 15°C and a relative humidity of 25%. The modified Swinbank formula in this case yields a flux of 274 w/m2, which in turn corresponds to a black body temperature of -9.5°C or a gray body temperature of 11.1°C.

**References**

W.C. Swinbank, "Long‐wave radiation from clear skies," *Quarterly Journal of the Royal Meteorological Society* 89.381 (1963): 339-348.

Mark A. Goforth, George W. Gilchrist, and Joseph D. Sirianni, "Cloud effects on thermal downwelling sky radiance," *AeroSense 2002, International Society for Optics and Photonics* (2002).