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# PALM-3000 Conjugate Height Selection
# CIN #615

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## Revision Sheet

| Release No. | Date | Revision Description |
|---|---|---|
| Rev. 0.1 | 01/10/07 | Initial draft by R. Dekany |
| Rev. 1.0 | 01/25/07 | Updated with comments from M. Troy; new section on scintillation |
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# Contents

# 1 GENERAL INFORMATION

## 1.1 Purpose

This document is intended to document the rationale for our choice of PALM-3000 conjugate height location.

## 1.2 Definitions

| | |
|---|---|
| Conjugate Height | The optical conjugate distance above the primary mirror. To convert to altitude above sea level, add 1,550 meters. |

## 1.3 Acronyms and Abbreviations

| | |
|---|---|
| AO | Adaptive Optics |
| DM | Deformable mirror |
| HOWFS | High-order wavefront sensor |
| LGS | Laser guide star |
| LOWFS | Low-order wavefront sensor (for PALM-3000 indicating tip/tilt/focus sensing) |
| NGS | Natural guide star |
| PALAO | The original NGS AO system at Palomar commissioned in December 1999 |
| PALM-3000 | The visible light AO upgrade to PALMAO |
| PALMAO | Upgrades to PALAO, particularly after the April 2003 upgrade |
| PALM LGS | The laser guide star upgrade to PALMAO |
| PALM LGS+ | The (potential) PALM LGS sodium laser upgrade from 6-8 W to 20-30 W |
| PALM/SWIFT | The optical re-layout of the PALM LGS bench to accommodate Oxford SWIFT (and potentially the AMNH P1640) |

## 1.4 Points of Contact

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# 2 BACKGROUND

## 2.1 Introduction

Although not intended to be operated as such, PALM-3000 is in fact a multiconjugate adaptive optics system. Because we 1) do not wish to degrade transmission with a reimaging stage, and 2) we believe packaging a reimaging stage would be difficult, it is our intention to maintain both the P3K woofer and tweeter mirrors in a single optical space.

To first order, we are attempting to mitigate the deleterious effects of this multiconjugate situation for narrow-angle precision wavefront AO, not trying to design for wide-field MCAO correction. In this way, we are rather distinguished from Gemini South MCAO (optimized for MCAO benefit) and Gemini GPI (which reimages its woofer and tweeter in two separate optical spaces, so each can be made optically conjugate to the telescope primary mirror.) Future researchers may devise control strategies to exploit the multiconjugate nature of PALM-3000, but this objective is not supported by our current science case[1].

## 2.2 Assumptions

Installation of the P3K tweeter DM is hoped to involve moving only flat optical surfaces, so that the OAP relay and instrument locations need not be adjusted (to first order, at least).

We deem the T5 (and more recent P18) Palomar MASS/DIMM data to be an accurate description of the typical $C_n^2(z)$ profiles over Palomar. These show that the site is often dominated by a strong low-altitude layer (0 - 500 m), with occasional strong turbulence at about 8 km above the site (associated with the tropopause and jet stream). This model has an average $r_0$ (0.5 $\mu$) = 0.092 meters and $\theta_0$ = 2.93 arcseconds (where $\theta_0$ is the finite aperture isoplanatic angle.)

We believe that the single optical space in P3K need not be collimated. With sufficient care, we believe we can align the two DM pupils in a vergent beam, if there was shown to be optical layout advantages to doing so (confirmed as resulting in acceptable relay aberrations.)

## 2.3 Constraints

The Xinetics tweeter DM is being developed with 66 actuators across the mirror diameter, on 1.8 mm pitch. The uncertainty on the actual (delivered) pitch is approximately 10%. P3K intends to use 62 subapertures across the telescope pupil, as well as control a single additional guard ring outside the pupil.

We wish to minimize cost of the P3K optical bench upgrade, seeking to use the existing optical bench and 8" diameter OAP pair in the new layout.

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[1] Dekany, R., PALM-3000 Science Requirements Document, Caltech Instrument Note #612, Release 1.0.

## 2.4 PALM-LGS mirror conjugate heights

The as-designed conjugate heights for PALM LGS are given by[2]:

| | |
|---|---|
| Conjugate location of FM1 in current system: | 10.1 km above M1 |
| Conjugate location of FSM in current system: | 4.0 km above M1 |
| Conjugate location of OAP1 in current system: | 2.2 km above M1 |
| Conjugate location of DM-349 in current system: | 0 km (at M1) |
| Conjugate location of FM2 in current system: | 1.55 km below M1 (-1.55 km) |
| Conjugate location of OAP2 in current system: | 3.0 km below M1 (-3.0 km) |
| Conjugate location of SSM1 in current system: | 7.0 km below M1 (-7.0 km) |
| Conjugate location of SSM2 in current system: | 13.8 km below M1 (-13.8 km) |

# 3 BEAM WALK

It will be important in subsequent calculations to keep in mind the magnitude of the beam walk as a function of field angle, conjugate location, and optical space. The basic compression of the 5,080 mm diameter telescope to the 112 mm PALMAO pupil diameter is $m_{pupil} = 112/5080 = 0.02205$. The magnification of angles from sky to collimated pupil space is therefore 1/0.02205 = 45.357. The beam walk within the collimated optical space of the DM, therefore is given by,

$$beam\ walk_{physical} = \theta_{sky} * h_{sky} * m_{pupil}$$

where theta is in radians. Converting to arcseconds, we have,

$$beam\ walk_{physical} = \theta_{sky}('') * h_{sky} * 1.069\times10^{-7}$$

There are several important field angles to consider. The typical field of view of a high-contrast observation (encompassing the outer working angle of P3K and a bit more) is 4 arcseconds radius; the corner of the (40 arcsec x 40 arcsec) PHARO array in wide field mode is 28.2 arcseconds radius; and a desirable field of regard (patrol range) for tip/tilt sensing is 60 arcsec radius (120 arcsec radius as an upper limit goal). For the 60 arcsec field point, the physical beam walk in the collimated AO space is 6.414 mm per km of conjugate height.

# 4 CONJUGATE ENVELOPE

## 4.1 Beam Walk Induced Anisoplanatism (BWIA)

Because our DMs will be at different conjugate heights, any control applied to optimize the wavefront error (or maximize image contrast) for an on-axis point will be incorrect for any off-axis field point. While beams from all field points overlap at the system pupil, these beams will separate at all other conjugate heights, leading to a field dependent error, beam walk induced anisoplanatism (BWIA).

The magnitude of BWIA is estimable by modeling the impact of beam walk on the mirror as being comparable to the equivalent beam shear in the atmosphere that leads to anisoplanatism error. For a conjugate height of 4.0 km, the beams heading toward the center and corner of the PHARO FoV (28.2 arcsec) are sheared by 0.547 meters on the sky.

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[2] Dekany, R., Informal technical memorandum dated January 15, 2003

The impact of BWIA is then estimated as comparable to an anisoplanatic error

$$\sigma_{aniso} \cong 0.7 \left( \frac{\Delta x}{r_0} \right)^{\frac{5}{6}} [rad]$$

where the 0.7 arises from the finite 5 m aperture at Palomar (the original analysis assumed infinite aperture). Using $\Delta x = 0.547$ m and $r_0 = 0.092$ m (at a wavelength 500 nm), we find the wavefront error due to beam walk for a 4 km conjugate is approximately:

$$\sigma_{\text{beam walk, 60'' field point}} = 86 \text{ nm rms}$$
$$\sigma_{\text{beam walk, PHARO}} = 46 \text{ nm rms}$$
$$\sigma_{\text{beam walk, 4'' field point}} = 9 \text{ nm rms.}$$

[Note, the effect of beam walk induced anisoplanatism will typically be greater than atmospheric anisoplanatism whenever the deformable mirror is conjugated above the mean turbulence height (well below 4 km at Palomar.)]

The impact of BWIA on the patrolling LOWFS performance will be to degrade the Strehl ratio of the field star, increasing tip/tilt residual error and reducing accessible sky fraction. As a rule of thumb, for Strehl ratios of about 60%, the fractional change in rms wavefront error is the same as the fractional change in Strehl ratio. Thus an additional 86 nm rms, added to 180 nm rms, results in 200 nm rms; with this ~10% increase in wavefront error resulting in ~10% decrease in Strehl (from 60% to 50% H-Strehl in this case). While this is not devastating, to maximum sky fraction, we would prefer the separation between Woofer and Tweeter DM's to be less than 4 km.

Since BWIA evolves rapidly with time it is not expected to interfere with P3K's science goal of $\sim 10^5$ contrast between peak intensity and minimum flux at the bottom of the dark hole cleared out of the PSF. Over a 4 arcsec radius FoV, the characteristic averaging time is estimated as the wind crossing time for the beam-walk distance of ~0.078 meters. (This is 150 milliseconds for a 5 m/s turbulence-weighted wind speed.)

Given the relatively benign effect of beam walk we can ask if the FM2 conjugate (only -1.5km below ground) is acceptable. Following the above argument, we find ~20 nm rms at the corner of PHARO's field of view, making this potentially interesting. However, given that we know the *average* turbulence height is not at 0 km height (e.g. at M1), we intuitively feel positive conjugates are better then negative ones. (In fact, if we chose the right positive conjugate, we could actually reduce anisoplanatism.)

A simple analysis, assuming a seasonal mean turbulence height of 500 meters (defendable based on T5 MASS/DIMM data), would suggest 0.5-(-1.5) = 2km below mean turbulence is better than (4.0-0.5) = 3.5km above mean turbulence.

Finding this acceptable at the corner of the largest FoV, we adopt a tolerance for the location of *either* of the P3K DMs to lie in the conjugate height range of -4.0 km to 4.0 km, with a goal of minimizing the absolute conjugate distance from the primary mirror (h = 0 km). In practice, this constrains the optical conjugate to the space between the PALM LGS FSM and FM2, if collimated space is preserved. Small vergence in this space may be acceptable if this can be shown to be necessary.

# 5 MIRROR ORDER

## 5.1 Tweeter DM Diameter

The choice of which mirror to place at the pupil appears to be trumped by the fact that the Tweeter DM is being designed to have a 112 mm pupil inscribing 62 illuminated subapertures (1.806 mm/actuator; Xinetics is working toward 1.8 mm pitch).

If the Tweeter DM were placed at 4 km conjugate, the maximum PHARO field corner beam walk of 0.547 meters (on-sky) would correspond to approximately 12 mm = 6.7 actuator physical shift on the DM. Since we envision only one guard ring outside the design pupil diameter, this means that the beam heading for the corner of PHARO's field would have walked off the Tweeter DM's active area by 5 actuators (out of 62) (and in doing so, possible off the mirror itself into vignetting). An example tip/tilt patrol field of regard of 60 arcsec diameter would walk off the DM by 25.5 mm, or 23% of the pupil. In other words, the Tweeter DM will simply be too small to place at 4 km conjugate without significant vignetting, particularly over the LOWFS patrol range.

For an optic placed at the -1.5 km conjugate, the physical beam walk would be only 4.5 mm at PHARO's corner, which may be acceptable walk-off and/or vignetting. Over a 60-arcsec radius field of regard, the beam walk is less than 10 mm, or about 9% of the pupil diameter, resulting in acceptable vignetting in the patrolling LOWFS. Over a 4-arcsec radius FoV, the physical walk at -1.5 km conjugate is only 0.64 mm, or about 1/3 of a Tweeter actuator pitch (1/11 of a Woofer DM pitch).

## 5.2 Scintillation

From Kolmogorov theory, we know that scintillation variance is proportional to the 5/6 moment of turbulence[3] and therefore arises only from turbulence removed from the collecting aperture. If we apply a phase conjugation at a location not at the telescope pupil, we can expect therefore to induce additional scintillation that was not present in the original wavefront.

The question then arises, is it objectionable to apply a large fraction of the correction (such as might be expected of the Woofer DM) at a non-zero conjugate height. Conservatively, we will assume that *all* of the correction is applied at finite conjugate height, $z_0$.

The fractional intensity variation dI/I for the beam is described by the scintillation index[3]:

$$\text{Scintillation index} = \sigma_I = \text{sqrt}(<[ I - < I >]^2>/< I >) = \text{sqrt}\ (4\sigma_\chi^2) = 2\ \text{sqrt}\ (\sigma_\chi^2) = 2\ \text{sqrt}\ (0.5631\ k_0^{7/6}\ \mu_{5/6})$$

Where $\mu_{5/6}$ is the 5/6th altitude moment of turbulence and $k_0 = 2\pi/\lambda$. To evaluate the $\mu_{5/6}$ for the atmosphere, we perform the height-weighted integral as usual. To evaluate the impact of all correction being performed at conjugate height, h, we assume $C_n^2(z) = C_n^2$ (full) * $\delta(z - h)$, where $C_n^2$ (full) is the integral of the atmospheric turbulence over all altitudes.

For a value of $r_0 = 0.092$, the change in scintillation index due to (full) correction is an increase from 0.36 to 0.53 for correction at 1.5 km and from 0.36 to 0.69 for correction at 4 km (all for the standard T5 Palomar $C_n^2(z)$ model and lambda = 0.5 microns). If we interpret the impact on Strehl ratio ($\exp(-\sigma_\chi^2)$) as an equivalent wavefront error in J-band (1.25 microns), we can alternatively say the error grows from 21

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[3] Sasilea, Electromagnetic Wave Propagation in Turbulence, Springer-Verlag, Berlin, (1994).

nm to 31 nm for 1.5 km conjugation and 41 nm for 4 km conjugation (all values rms). In reality, some of the turbulence will be corrected at the pupil, so these scintillation estimates are upper limits.

As far as scintillation is concerned, we would prefer as much correction to be applied as near as possible to the telescope pupil as possible, yet the impact of large-stroke woofer correction at 1.5 km conjugate (and probably even 4 km) appears acceptable. Correction at -1.5 km conjugate is expected to have no worse impact than at +1.5 km, as there is less physical propagation distance to the final focus.

## 6 FAST STEERING MIRROR (FSM) CONSIDERATIONS

PALM-3000 still requires a separate tip/tilt mirror to offload the large tip/tilt signal in the turbulence (insufficient stroke in the DM's). Since this (large) mirror needs to fit onto the bench, we are inclined to not move it from it's current location. Specifically the FM2 location is likely to be a difficult fit for the existing FSM mount, and any motion too far from the pupil will result in lower on-sky throw (for finite FSM stroke) and potential misregistrations between DM's and WFS's.

Because of these issues, all else being equal, we favor leaving FSM where it is.

## 7 CONCLUSIONS

Based on simplicity, vignetting, scintillation, and our tip/tilt mirror constraints, we favor as a minimum effort solution that the Tweeter DM be located at the telescope pupil (old DM position), and the Woofer DM be moved to the current FM2 position (at approximately a conjugate height of -1.5 km).

Since this may result in somewhat worse anisoplanatism, we may wish to consider slight changes to the vergence of the optical space to 'split the difference', if time allows (e.g. Tweeter DM conjugate to +0.5 km and Woofer DM conjugate to -1.0 km).