AVAILABILITY OF GUIDE STARS IN DARK CLOUDS

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OCTOBER 1995

1.0 Overview

One of the top science goals for the Gemini telescopes has been to conduct cutting-edge research involving spectroscopy and imaging in obscured star formation regions. Targets like the near-by molecular clouds in Orion, Taurus, and Ophiucus represent high priority science targets at infrared wavelengths, where it is possible to penetrate through the dust enshrouding these objects and observe forming stellar systems, disks, and potentially substellar objects. With the heavy emphasis on the overall Gemini telescope design of low emissivity, high throughput, and high performance imaging, a quite natural scientific niche that Gemini stands to uniquely fill is dark cloud research. Accordingly, a key question that the IGPO has been investigating, in coordination with the Acquisition and Guiding/Adaptive Optics and Infrared Instrument Science Working Groups is the viability of providing adequate tip/tilt correction signals to the Gemini secondary or AO systems in dark clouds.

Throughout most of the design stage of the Gemini NIRI and NIRS the on-instrument WFS has been assumed to be based upon a small format, low noise, high speed CCD. Top level performance has been set by the SRD requirement to acquire a guide star with 90% confidence in the 3 arcmin field of view of the on-instrument WFS (OIWFS) at the Galactic pole. For R-band sensing and typical sampling rates of ~100 Hz this translates into stars as faint as ~18.5 mag. In the context of dark cloud observations, the natural questions that stem from this baseline performance level include:

1. Are there enough guide stars at R and I in dark clouds to support wavefront sensing with CCDs?

2. If not, are there enough guide stars at J and H to support wavefront sensing with near infrared detectors and are those stars bright enough to provide adequate correction with technologically viable arrays?

3. Finally, what type of performance can one expect at the Galactic pole, i.e., can a near infrared WFS be used as a complete substitute for a CCD based sensor?

2.0 Optical Guide Star Availability

To help answers these questions, Figure 1 is an example of a “classic” nearby star formation region, ρ Oph. Shown is an ~8°x8° photograph of the region, together with a guide star chart generated from the HST guide star catalog (HST-GSC), which is complete down to the V~15-16 mag level. Down to the limits of the HST-GSC there are

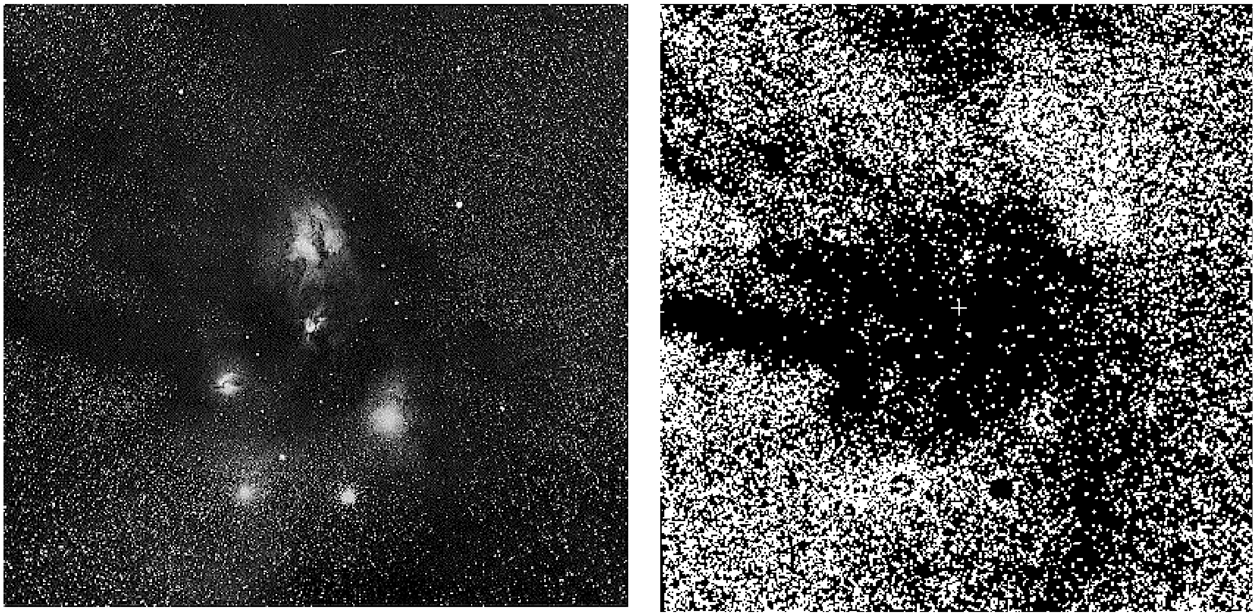

Figure 1 - Seen in the left is an 8°x8° photograph of ρ Oph, depicting large regions of highly obscured guide star search fields at optical wavelengths. The corresponding field as generated by the HST guide star catalog is shown on the right.

large areas that even the PWFS's, which have a 14 arcmin search diameter, may not be able to find optical guide stars. Figure 2 shows the field surrounding an embedded infrared source, L1689, roughly centered in the ρ Oph nebula. It was derived from the STScI digitized sky survey and shows stars in a ~25x25 arcmin area down to ~20.5 mag. This image was derived from a blue plate in the survey and demonstrates that for this area there are only a few guide stars in the entire field shown. Clearly, finding optical guide stars in this area would be a problem for a sensor restricted to the 3 arcmin diameter search field of the OIWFS. These results are not surprising since it is well known that the optical extinction in the core and dense filaments of this system and other nearby star formation regions is several tens of magnitudes. Furthermore they are consistent with the experience of many astronomers working on 4 m class telescopes in dark clouds using conventional (e.g., ISIT) guide cameras with typically a few arcmin fields of view. Finding guide stars under such conditions is generally quite challenging.

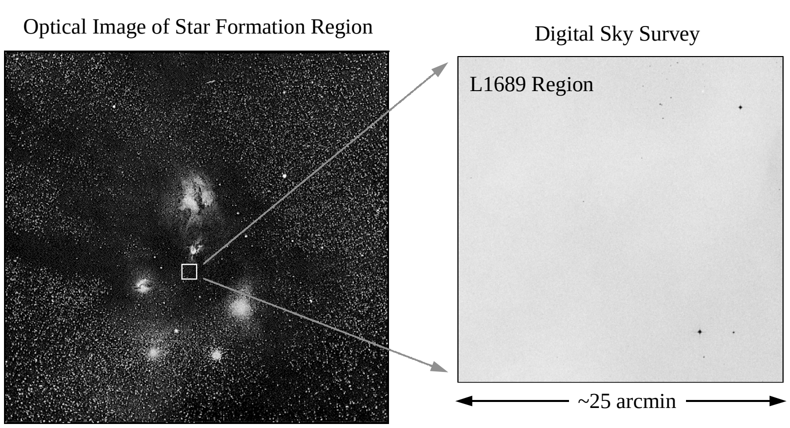

Figure 2 - The core of r Oph is shown with in the form of a ~25' extract from the STScI digital sky survey. Down to the ~20.5 mag limits of this plate, only a few stars are evident in this image, illustrative of how hard it may be to find optical guide stars in these regions.

In order to further quantify the availability of guide stars at red/optical wavelengths, Tom Jarrett kindly provided the IGPO with a source catalog for the ~25x25 arcmin region depicted in Figure 2. The

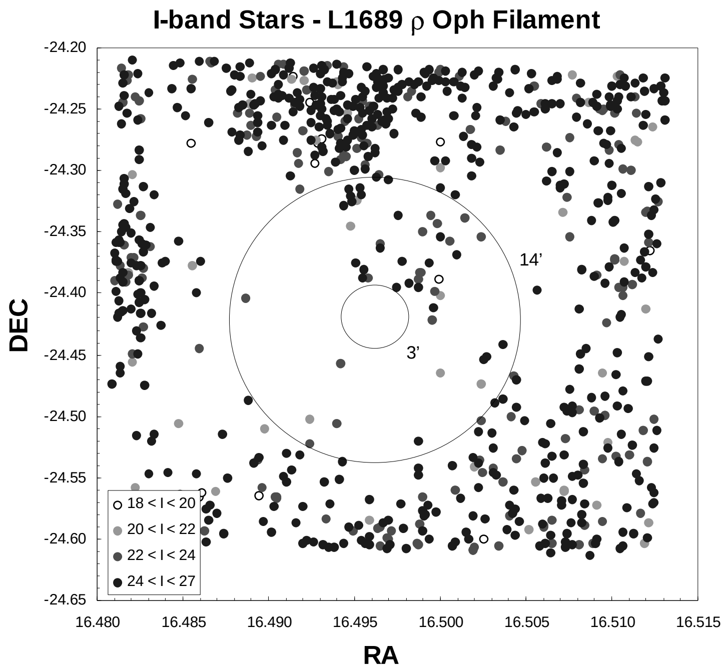

Figure 3 - A star chart of a typical star formation region in ρ Oph is shown, as derived from deep I-band imaging by Jarrett (private communication). This is the same region shown in Figure 2. The fields of view for the OIWFS and PWFS's are shown. Significant star densities for wavefront sensing are realized until extremely faint (R or I > 24 mag) are reached, which would place CCDs well into the read-noise dominated regime.

catalog was derived from extremely deep R and I band imaging (targets as faint as 27 magnitude are listed). Figure 3 shows the I-band star chart (which represents a "best case" since it is the reddest data set), as synthesized from Jarrett's data. The sizes of the OIWFS and PWFS fields of view are overlaid on this chart. From these data it appears that even at red sub-micron wavelengths it will be necessary to go down to extremely faint (~24 mag) levels before significant numbers of guide stars become available, which would render CCDs useless given even the ~5 e- read noise expected for these sensors.

Expanding the analysis further, a total of 33 embedded IRAS targets scattered around ρ Oph and Taurus were examined in the STScI "Digital Sky Survey" catalog available on-line now from a number of sources. This catalog goes down to ~20.5 mag at blue wavelengths for ρ Oph and ~21.5 mag at red wavelengths for the Taurus region. Of the 33 targets examined, 6 had no optical guide star in the 3 arcmin field of view of the OIWFS, and 9 had marginal guide stars, where marginal means a star was barely visible or on the extreme edge of the OIWFS field of view. Hence a total of ~45% of these targets had no or at best a poor guide star available for optical wavefront sensing in what would be typical infrared science fields.

3.0 Infrared Guide Star Availability

To examine the question of how many infrared guide stars are available in ρ Oph, the IPAC/2MASS team generously supplied the IGPO images and a source catalog of recent scans of ρ Oph, completed in April 1995 as part of the general test program to develop acquisition and pipeline processing techniques.[*] The scans were made at J, H, and K_s and covered an area of ~0.5°x6.0° with limiting magnitudes of 16.5, 16.0, and 15.5 respectively provided in the source catalogs. Figure 4 shows a typical J-band 2MASS scan segment in ρ Oph and illustrates the large number of

[*] Many thanks to Chas Beichman, Roc Cutri, Mike Skrutskie et al. for releasing this data to the Gemini project.

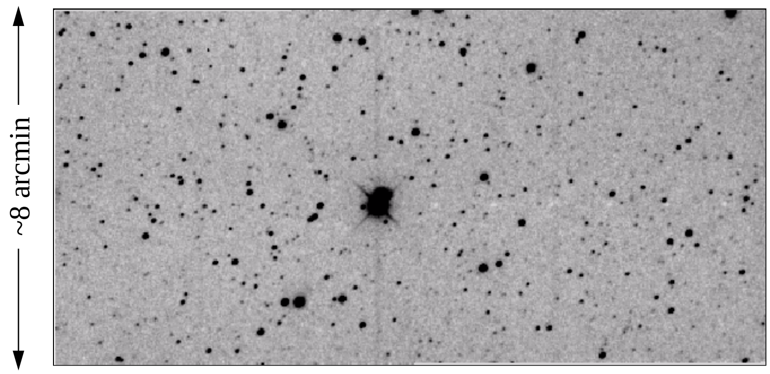

Figure 4 - A typical ρ Oph scan segment from the 2MASS project is shown. This scan was made at J. Stars as faint as ~16.5 mag are detected. Note how a multitude of stars are evident in such near-infrared images, compared to optical images going much deeper.

infrared stars available in a field that would typically be devoid of stars at optical wavelengths. Given the ~8x20 arcmin size of the field, compared to the 3 arcmin field of the on-instrument wavefront sensors, it is fairly easy to see how the probability of acquiring a guide star in this region is very high. In fact, averaging across the entire cataloged area yields a >99% probability that a star could be found at J, H, or K_S in a 3 arcmin diameter patrol field.

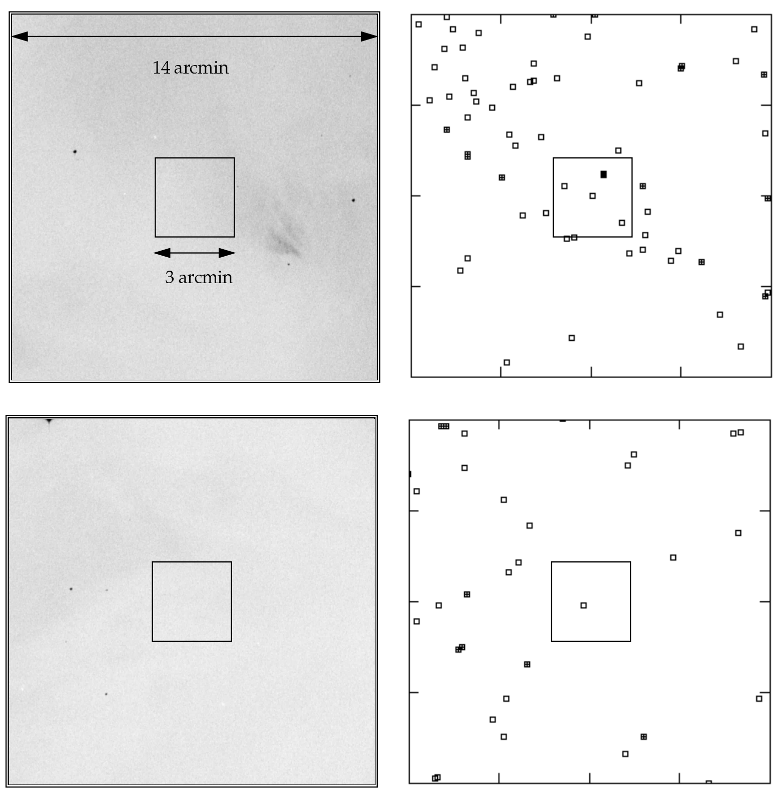

Figure 5 - Examples of typical embedded ρ Oph IRAS sources as viewed with the STScI digital catalog images (left) and corresponding J-band star charts derived from 2MASS scans (right) are shown. Filled boxes correspond to J < 13 mag sources. For the 3 arcmin field of view of the OIWFS's there will be significant problems finding adequate guide stars in these highly obscured areas unless near-infrared wavefront sensing is implemented.

Figure 5 shows a pair of embedded IRAS fields as viewed from the HST Digital Sky Survey and the corresponding 2MASS source catalog at J. Needless to say going to H or K_S only increases the number of infrared guide stars available in these highly obscured fields. These side by side comparisons demonstrate the paucity of optical stars available around infrared science targets in ρ Oph as well as the large number available for peripheral and near-infrared on-instrument wavefront sensing. Assessing a number of these embedded IRAS sources in the 2MASS catalog showed that, in the worst case, the embedded source always appears at J or longer wavelengths. Additionally, in most cases at least one additional guide star is available at J (the worst-case bandpass since extinction is the most severe) down to the previously mentioned 2MASS magnitude limits. In general there are at least 2 *optical* stars available for peripheral wavefront sensing, hence the problem of finding adequate guide stars does not appear to be as severe for the PWFS's.

4.0 Near-infrared Wavefront Sensing

With the availability of near-infrared guide stars in typical dark cloud science fields established, F. Gillett examined the performance level of T/T/F correction theoretically achievable with OIWFS's that are sensitive to 1-2.5 μm radiation. F. Gillett's report "Near IR WFSing for Gemini" appears in a separate technical note (TN-PS-G0031) hence only the major points of his analysis will be presented here.

Some of the general advantages associated with NIR versus optical wavefront sensing include reduced susceptibility to differential atmospheric refraction between science targets and reference stars, better performance under moonlit and twilight conditions, and a generally tighter PSF available for making centroiding measurements. Due to the typical spectral energy distribution of guide stars, one expects roughly twice the number of photoelectrons being available at J or H than R for the same guide star acquisition probability at the Galactic pole. Combining this factor with other assumptions about noise, sampling, etc., leads to typical centroid errors that are nearly a factor of 2 lower at J or H versus R. More specifically, at the Galactic pole a near-infrared wavefront sensor outperforms an optical sensor so the advantages of the former apply to the entire sky, not just dark clouds.

Clearly this approach relies on high performance near-infrared sensitive arrays. So-called Fowler sampling can be used to reduce read noise by factors of 2-3 over single-read noise levels while still yielding frames rates that are fast enough to achieve good correction for the atmosphere and wind shake (>200 fps). Germanium appears attractive since it is not intrinsically sensitive to thermal wavelengths (hence packaging is simplified) and has a lower capacitance than InSb or HgCdTe, thereby reducing read noise. For the 5 e- read noise assumed in F. Gillett's analysis a Ge 256^2 array based upon the SBRC 463 MUX with 4 reads could possibly be used. Note that the Hawaii 1k array manufactured by Rockwell may also be able to support wavefront sensing through the use of multiple reads of a small subarray. K. Hodapp reports lab measurements using multiple non-destructive reads have yielded ~5 e- noise with the Hawaii array, which is adequate to reach the desired T/T compensation level.

5.0 Summary

Based upon this assessment it appears that for the "classic" star formation region ρ Oph there is an abundance of near-infrared guide stars of sufficient brightness to yield good tip/tilt correction. If optical guide stars are relied upon to support observations there will be significant performance degradation that would have to be factored into infrared observations. No performance degradation would be suffered if NIR wavefront sensing is used. Table 1 lists telescope performance as a function of control loop closure, excluding atmospheric effects. Assuming the telescope must be run without any guide stars and only from look-up tables, images with ~3/4" resolution will be possible at 2.2 μm. Closing the guide loop reduces point source widths by about a factor of 2 and tip/tilt corrections reduce them by a factor of ~2 again. It is important to note that in general it is possible to acquire a guide star for the peripheral sensors, due to the 14 arcmin field these sensors patrol and the fact that long term updates of the telescope alignment can be completed through relatively long integrations on faint stars. Also, some tip/tilt correction will be possible through the use of peripheral WFS stars, albeit at reduced performance due to anisoplanicity. Operating in such a mode may actually not be a serious problem at mid-infrared wavelengths, where diffraction effects are comparatively large, and tip/tilt corrections can be achieved over large field angles. But at near-infrared wavelengths there certainly would be a significant performance degradation if no guide stars are available for the on-instrument wavefront sensors. This is particularly true when adaptive optics are factored in, since anisoplanicity is a crucial factor in higher order corrections and having a guide star near the science target is important to achieve maximum strehls. Under the assumption that a laser system is used in combination with a near infrared on-instrument tip/tilt sensor, it should be possible to accomplish high performance near-infrared imaging and spectroscopy of embedded targets. This represents a unique and important scientific niche that Gemini could offer its user community.

Component	Open	Autoguider	Tip/Tilt	Focus	Active
Optical Design	0.065	0.065	0.065	0.065	0.065
Surface Errors	0.187	0.187	0.140	0.105	0.046
Optical Alignment	0.014	0.014	0.014	0.014	0.014
Self Induced Seeing	0.027	0.027	0.027	0.027	0.027
Dynamic Alignment	0.036	0.036	0.025	0.004	0.004
Tracking	0.732	0.332	0.056	0.056	0.056
RSS Totals	0.76	0.39	0.17	0.14	0.10

Table 1 - The predicted image quality for Gemini is shown as a function of closure of various control loops. Performance improves smoothly as additional loops are closed. Tip/tilt compensation provides ~5x better performance at 2.2 μm over open-loop tracking.