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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

A PROPOSED ASTRONOMICAL REFERENCE CATALOG OF INFRARED SOURCES

J.M. SORVARI
Group 38

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EXECUTIVE SUMMARY

1. INTRODUCTION

Measurements of stars at infrared (IR) wavelengths are potentially very valuable in a variety of defense-related programs, including the COBRA EYE Project (CE, formerly the Optical Aircraft Measurement Program). In practice the value of such measurements is compromised by deficiencies in the astronomical data base. A study panel was convened to examine ways of improving the situation.

The astronomical data base at IR wavelengths is not completely self-consistent, and adequate spectral data are not generally available. The number of suitable reference stars is smaller than is desirable, especially at longer wavelengths. The most homogeneous data set, the Infrared Astronomical Satellite (IRAS) observations, cannot adequately characterize variability or spatial extent. An alternate calibration strategy, use of chamber facilities, is satisfactory for some tasks but suffers several shortcomings.

The panel concludes that a catalog of stellar reference spectra can be custom tailored to meet the needs of defense-related programs.

2. DATA REQUIREMENTS

A set of target goals for data characteristics is presented. Attaining these goals would guarantee the ultimate accuracy of stellar calibration for any user program. However, questions of cost-effectiveness and practicability were ignored in setting these target goals.

Specifications were derived for each target goal by trading off cost-effectiveness and practicability against the impact on system performance. The result is a specification that defines a data set that can be created at a reasonable level of effort with minimal compromise of calibration accuracy.

3. TECHNICAL APPROACH

Building the specified catalog requires three types of data: precision radiometry, spectroscopy, and moderate-resolution imaging. The following approach to obtaining these data is defined.

The existing absolute calibration of Arcturus (α Boo) meets the accuracy requirement.

Analysis of IRAS data and other published data will provide some of the needed radiometric and spectroscopic data and will allow efficient selection of candidate standard stars.

Development of new instrumentation to support efficient observation with the required precision is necessary. Several generic designs appear appropriate. The most problematic part of the instrumental development is procurement of suitable detector arrays.

Observation for approximately 48 nights at suitable facilities should be adequate to provide the precision radiometry and imaging. Use of two independent facilities will allow verification of data precision and homogeneity. The observations should be spread over two years to ensure detection of variability.

Collection of supplemental spectroscopic data will have to be supported by airborne observations. Ten Kuiper Airborne Observatory (KAO) flights would be adequate if no other spectroscopic data are available. Utilization of archival data will reduce this requirement to perhaps five flights.

Creation of supplemental catalogs of stars normally considered inappropriate for use as standards, will be necessary because of the paucity of suitable stars at long wavelengths. Special techniques will have to be developed to deal with the supplemental stars.

4. RECOMMENDATIONS

The creation of a catalog of stellar reference spectra should be undertaken. The catalog would provide valuable support for a variety of programs. Instrumental development provides the greatest cost and schedule risks and will thus be the pacing task. The ground-based measurement task is low risk. Archival research would be of some benefit, even if the other tasks were not undertaken.

An ongoing low level of effort program of supporting observation should be established. It would provide the best means of handling the supplemental stars and would support other special circumstances at minimal cost.

Once the catalog is established, it will be easy to take advantage of future absolute calibration experiments. At least two such experiments are plausible.

5. SUPPLEMENTAL MATERIAL

A series of appendices contains explanations, derivations, and expansions of specific points in the main report.

Appendix A presents an outline of the suggested project. It is estimated that the scope of the project would include about twelve engineering years and cost about four million dollars exclusive of the detector arrays. The project would produce the final catalog three and a half to four years after the project began.

The absolute calibration (Appendix B) is based on a variety of methodologies. The two most important are direct comparisons with standard sources and measurement with respect to the sun via solar-type stars. The various methods agree to about three percent from 1 to 10 μm. The estimated errors double by 25 μm.

Spatial extent (Appendix C) is important because of its effect on the calibration of sensors, which are analyzed assuming point sources. To keep the error due to finite extent negligible, the stars must not exceed 4 μrad at 11 μm. The 4-μrad threshold can be regularly achieved at good astronomical sites using telescopes of 2- to 3-m aperture.

Spectral resolution (Appendix D) of the catalog affects the accuracy with which the user can calculate values of in-band radiance for particular passbands. The sensitivity of the calculation to the spectral resolution depends on the high-frequency spectral content of the stellar radiation and on the detailed structure of the passband. Since the spectral content of the stellar radiation offers no natural high-frequency cutoff, we base the resolution requirement on the structure of a typical application passband. Analysis in the Fourier domain leads to a requirement for a minimum resolution of $\lambda/\Delta\lambda = 30$.

Ultimately the catalog size will be limited by the number of suitable stars available. A preliminary list of candidate stars (Appendix E) was chosen from the literature, based on astrophysical characteristics that are likely to be associated with suitability for use as reference stars. There are 48 stars that are quite satisfactory through 10 µm but that average is somewhat too faint at longer wavelengths. Relaxing the selection criteria slightly provides an additional 18 brighter stars, most of which are probably variable to some degree. Many stars that do not meet the selection criteria will still be satisfactory, if not ideal, for use as reference stars.

The Detector Array Bibliography lists several articles from a symposium dealing with the development and astronomical application of IR detector arrays.

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PREFACE

The Study Panel was convened to discuss the use of astronomical data by the COBRA EYE Program and similar programs. The Panel held four scheduled meetings and exchanged considerable amounts of data between times. By and large we were able to achieve consensus on the problem and potential solutions. This report is an attempt to represent that consensus. Inevitably, individual panel members will differ on some specific details from the view reported here. Any omissions or misrepresentations of the panel's consensus are the responsibility of the chairman. The panel members are

E.E. Becklin
Institute for Astronomy, University of Hawaii

G.O. Burgess
Signature Studies and Analysis, MIT/Lincoln Laboratory

C.W. Engelke
Advanced Techniques and Systems, MIT/Lincoln Laboratory

T.F. Greene
Boeing Aerospace Company

J.P. Henry
Institute for Astronomy, University of Hawaii

G.H. Rieke
Steward Observatory, University of Arizona

J.M. Sorvari, Chairman
System Engineering, MIT/Lincoln Laboratory

ACKNOWLEDGMENT

This report contains more than a fair share of arcane mathematical notation and other typographical challenges. It is a pleasure for me to thank Mrs. Barbara Tremblay for effectively dealing with these.

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1. INTRODUCTION AND OVERVIEW

1.1 STATEMENT OF THE PROBLEM

Many defense-related programs have used astronomical data to support various program functions. The CE project is one such program. CE operations involve measurements of satellites and reentry vehicles (RVs) at Infrared (IR) wavelengths and includes stellar measurements in the test planning. These stellar measurements are an important part of the system calibration and also serve as test measurements for performance evaluation and training. Additional planned uses include mission-to-mission repeatability analysis and correlation of CE data with the results of other programs.

Programs such as CE project are dependent on the properties of the astronomical data. These data are obtained for a variety of astrophysical reasons and have properties that may be inappropriate for application to such programs. Because of the sometimes inappropriate data properties, application of astronomical data has fallen short of its potential contribution. There are two important problem areas. First, the quality of the published astronomical IR data is very irregular with only the best data being useful to most programs. In many instances this fact results in having to choose between having no stellar data or using poor-quality data. Second, the properties of the data are seldom well documented. and some rather arcane measurement units are used. It is all too easy for an outsider to misunderstand and misapply the data. The situation reflects both real physical limitations and rather great differences between the goals of the astronomical community and the application users of astronomical data.

This report presents the results of a study undertaken to address the use of astronomical data to support the CE project and a variety of current and proposed programs. The Study Panel examined the data quality needed to support generalized program goals, the extent to which the astronomical data can be improved, and the scope of the sort of program that would be needed to produce the best possible data base. Also this report includes estimates of user needs in the future and estimates of existing data quality. Appendices contain detailed explanations of specific points where deemed appropriate.

1.2 LIMITATIONS IN EXISTING DATA AND TECHNIQUE

1.2.1 Standard Star Networks

Absolute calibration at wavelengths from the visible through 11 μm is nominally determined to an accuracy of three percent (see Appendix B). As the intercomparisons of the several networks improve, it may become useful and desirable to make confirming and refining measurements. However, between 10 and 20 μm there are only nine primary standard stars that have been intercompared precisely and tied to the absolute calibration accurately. This sparseness of standards is a primary cause of error at long wavelengths. At 1 to 5 μm there are half-a-dozen standard star networks in common use, each of which contains 30 to 60 stars. Unfortunately, few of these networks are tied into the calibration accurately, and some of them have not been precisely compared with the others. The primary cause of calibration errors at these wavelengths is inconsistencies among networks, particularly inconsistencies in the underlying definitions of the calibrations. Finally, there is no satisfactory, comprehensive, "user-friendly" description of the networks and calibration.

1.2.2 Transformation to User Passbands

Most published astronomical magnitudes refer to broadband, integrated irradiance, similar to the values used in typical applications. Unfortunately, there are rarely sufficient data available to allow transformation of the astronomical data into the user's natural system. In addition, not all users are aware that such a transformation is needed, nor are they aware that out-of-band leakage in the user's system can severely compromise the value of stellar measurements made by the user. As a result, astronomical data are often inadvertently misused.

1.2.3 Data from the Infrared Astronomical Satellite

At 12 and 25 μm IRAS provides measurements of virtually all potential standard stars. For pointed observations the intercomparisons among stars appear to be accurate to a root-mean-square (rms) value of two percent or better. However, only three percent of the sky was covered in pointed mode. In the survey mode typical rms errors are four percent. The IRAS observations are obtained using a detector beam of three square arc min, so it is not possible to examine these data for possible multiple or extended sources within this resolution element. In addition, there is no useful spectral information on potential high-quality standard stars outside the broad photometric bands, nor are there adequate data to thoroughly assess variability of most stars.

1.2.4 Chamber Facilities

Over the years a considerable effort has been expended in the design and construction of ground-based calibration facilities for use in calibration of IR sensors. These calibration facilities all suffer from certain limitations. For example, the absolute accuracy of our knowledge of the test beam spectral radiant intensity is probably not known to better than five to 10 percent even at the 1-σ confidence level, and especially at the lower incidence levels ($< 10^{-15}$ W cm^{-2} μm^{-1}) and at longer wavelengths (> 10 μm). At least some chambers have suffered from large unplanned spectral variations (up to forty percent) within a several-micrometer-wide spectral interval between 5 and 25 μm. As sensors become larger, the cost of calibration chambers is becoming very large (several tens of millions of dollars). Finally, calibration with ground-based chambers characteristically occurs months or years before flight. There is always the question of whether the responsivity of the sensor has changed between the calibration time and the instant of target viewing.

To be sure, chambers do offer some capability that calibration stars cannot provide. A wide range of test conditions can be explored. Any or all detectors can be irradiated at various target incidence levels while experiencing various background levels. The effects of sensor temperature and irradiation history can be measured and sensor operating parameters can be optimized.

1.3 CONCLUSIONS OF THE PANEL

The Panel concludes that the community of application users would be well served by the creation of a suitable Astronomical Reference Catalog (ARC) of IR spectra. Such a catalog could support most upward-looking IR sensor programs. Each program would have available to it at low cost an already-deployed and well-characterized set of calibration sources that could be utilized in an ordinary operational scenario.

2. DERIVATION OF REQUIREMENTS

2.1 TARGET GOALS

A set of generalized goals was presented and discussed. These goals are based on recent and current defense-related programs and projections for growth. Cost-effectiveness and practicability were not considered in setting these goals. Where appropriate, comments on sensitivity to shortfalls are included.

2.1.1 Number of Stars

There should be a minimum of 300 stars distributed uniformly over the sky. Many sensors will have limited maneuverability. Insufficient star density will mean lack of support for these programs.

2.1.2 Positional Accuracy

The positional accuracy is better than 5 μrad.

2.1.3 Spatial Isolation

No contaminating source exists within 0.5°.

2.1.4 Spatial Structure

The spatial extent should be less than 2 μrad. Because many programs use AC-coupled scanned detectors, images differing from unresolved point sources will give rise to calibration error.

2.1.5 Spectral Range

The spectral range is from 2 to 25 μm.

2.1.6 Spectral Data

Spectral data must be sufficient to allow accurate synthesis of an arbitrary user in-band radiance.

2.1.7 Relative Accuracy

The relative accuracy is one percent (1σ). This is the random error in the data and is a measure of the uniformity of the catalog.

2.1.8 Absolute Accuracy

The absolute accuracy is two percent (1σ). This is the estimate of the measured-minus-true value and would be a systematic error for the catalog as a whole.

2.1.9 Documentation

Calibration must be clearly and fully traceable. Historically, data from the astronomical literature have been improperly used due to unstated assumptions and characterizations and to unclear calibration heritage.

2.1.10 Star Variability

Star variability must not be a source of error. If the variability of a star can be sufficiently well characterized that its current brightness is known to within the constraint of 2.1.7, then it may be used.

2.1.11 Flux Range

The stars chosen for the catalog should have astronomical magnitudes in the following ranges:

$$-7 < Q\ (\sim 21\ \mu m) < -3$$
$$-5 < N\ (10.6\ \mu m) < -1$$
$$0 < M\ (\sim 5.0\ \mu m) < 4$$
$$0 < L\ (3.5\ \mu m) < 4$$
$$0 < K\ (2.2\ \mu m) < 4$$
$$0 < J\ (1.3\ \mu m) < 4$$

Use of stars brighter than this by user programs is likely to give rise to problems with nonlinearity. Use of stars fainter than this will result in low Signal-to-Noise Ratio (SNR).

2.2 DATA SET SPECIFICATION

This set of specifications represents practicable, state-of-the-art measurement capability. Where appropriate, comments are provided discussing differences from the target goals of Section 2.1.

2.2.1 Number of Stars

Initially, the number of stars at each wavelength is 100, distributed as uniformly as possible north of declination −40°. For randomly distributed stars this number would yield a mean Nearest Neighbor Distance (NND) of 9.4°. The number of stars grows as NND^{-2}, so a significant reduction of NND requires many more stars. The number of stars is initially low, to allow a basic star network to be set up reasonably quickly. More stars can be added relatively easily as part of an ongoing observation program utilizing the established basic star network.

2.2.2 Positional Accuracy

The positional accuracy is better than 5 μrad, current epoch.

2.2.3 Spatial Isolation

No source exists that could lead to misidentification within 0.5°. No contaminating source exists at the two percent level within 1 mrad.

2.2.4 Spatial Structure

The spatial extent must be less than 4 μrad for the primary catalog (see the discussion in Appendix C).

2.2.5 Spectral Coverage

The spectral coverage is from 2 to 25 μm.

2.2.6 Spectral Data

The resolution is $\lambda/\Delta\lambda \geq 30$ (see the discussion in Appendix D).

2.2.7 Relative Precision

The estimated error of the in-band radiance synthesized according to the recipe in the User's Manual, expressed in terms of the reference object, is shown in Figure 2-1.

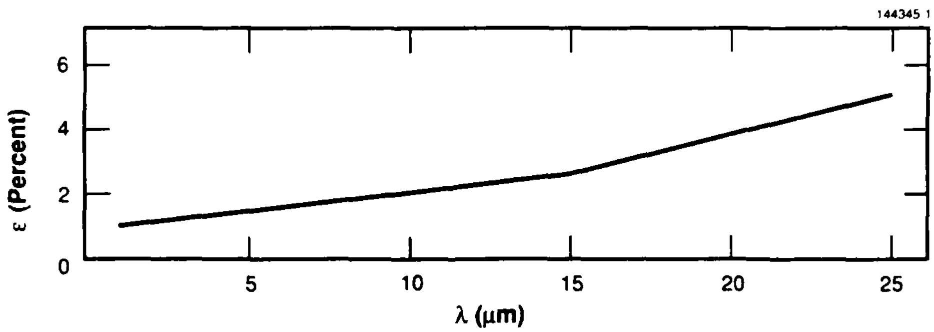

Figure 2-1. Relative accuracy as a function of wavelength.

2.2.8 Absolute Accuracy

The estimated error of the reference object, expressed in physical units (W cm^{-2} μm^{-1}), is shown in Figure 2-2.

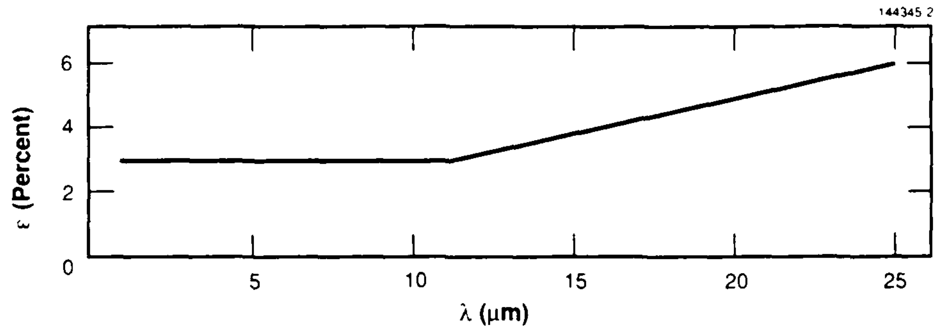

Figure 2-2. Absolute accuracy as a function of wavelength.

2.2.9 Documentation

A Data User's Manual shall be published along with the Astronomical Reference Catalog. It shall contain at least the following items:

a. A thorough exposition of the calibration, including explanation of how future calibration experiments can be incorporated.

b. A complete description of the error characteristics of the catalog.

c. Specific instructions for the synthesis of in-band radiance for an arbitrary user response profile. This must include explanation of the effects of out-of-band leakage.

d. Specific instructions for correcting for precession, nutation, and aberration.

e. Instructions for use of the supplemental stars.

2.2.10 Star Variability

The supplemental list may contain variable stars subject to the constraint that it must be possible to adjust the data on the basis of a limited set of measurements so that the criterion of 2.2.7 is met.

2.2.11 Flux Range

Stars chosen for the catalog shall have astronomical magnitudes in the following ranges:

$$-7 < Q < 0$$
$$-5 < N < 0$$
$$0 < M < 4$$
$$0 < L < 4$$
$$0 < K < 4$$
$$0 < J < 4$$

3. TECHNICAL APPROACH

Three sorts of data will be needed to support the requirements in Section 2.2:

a. Precise radiometry in selected bands obtained over a two year period will provide a framework of fixed reference points and will allow variability to be detected.

b. Relative spectra at moderate resolution will allow detailed interpolation between the fixed points. The absolute accuracy of these data is not critical.

c. Images taken in the 10- to 12-μm atmospheric window with 1-arc sec pixels over a 1-arc min area will provide spatial extent data and will allow elimination of potentially contaminating or confusing sources. High radiometric accuracy of the images is not needed.

The recommended approach to creating the stellar data set is an extensive program of ground-based spectroradiometric measurement and broadband imaging supplemented by smaller programs of airborne spectrographic measurement and archival research. The ground-based observations would be carried out at one or more of the major academic research observatories. Instrumental development would be necessary. No new calibration experiments are suggested since currently existing calibrations, properly integrated, support the requirements in Section 2.2. The most reliable data set would be obtained by running two independent ground-based programs with a partial overlap of observations.

A continuing program of ground-based observations would also prove beneficial. The ongoing observations could be used to add stars to both the standard and supplemental catalogs and would provide the additional data needed to adjust specific supplemental stars for current or recent use by application user programs.

3.1 CALIBRATION

Standard star networks are traditionally defined in terms of a single "super-standard." For years Vega (α Lyr) has played this role in the optical calibration. The precision of the intercomparison of the network stars with Vega can be improved independently of adjustments in the absolute calibration, and vice versa. In addition, the history of changes in either part of the system can be traced relatively easily.

Unfortunately, Vega cannot play a similar role in the IR. It is not bright enough to be measured with high accuracy at the longer wavelengths. Furthermore, IRAS data have shown it to be surrounded by a particle cloud that contributes an extended far IR component. Thus Vega is deficient with regard to both criteria 2.1.4 and 2.1.11 for a high-quality standard. We propose that the traditional role of Vega be assumed by Arcturus (α Boo) for the IR system. This star is well studied and appears to meet all the criteria for a super standard. In addition, it is reasonably close to Vega in the sky, making intercomparisons relatively easy. The current calibration of the spectral radiance of Arcturus meets the requirement 2.2.8.

3.2 ARCHIVAL ANALYSIS PROGRAM

By careful data reduction of the IRAS survey data it should be possible to improve the accuracy of the measurements of the proposed standard star network. The largest advance will come through taking account of the cross-scan variations in detector response. These variations were measured during the mission by repeated scans of the planetary nebula NGC 6543. They have peak-to-peak amplitudes of about ten percent. An accurate model of the satellite has been generated at Jet Propulsion Laboratory (JPL); it would allow determining the scan coordinates of each star relative to the detectors. Combining these two pieces of information should result in intercomparisons at an accuracy approaching that of the pointed observations, i.e., rms error of approximately two percent.

Other archival data would also be useful in the selection of candidate standards and would provide a limited amount of spectral data.

3.3 INSTRUMENTAL DEVELOPMENT

In order to perform the observations needed to support the requirements in Section 2.2, it will be necessary to develop new instrumentation. We believe that the best prospect is provided by array-based instruments. Not only does use of an array fulfill the need for imaging, but it will also support high-precision spectral and radiometric measurement. Astronomical experience with detector arrays is only now being extended into the longer wavelength portion of the spectral coverage required by this program. In the 1 to 5 μm range, however, a large amount of high-quality data has been collected. Appendix F lists several articles from a recent symposium addressing astronomical use of detector arrays. It is noteworthy that although radiometry has been traditionally performed using single-channel instruments, arrays offer potential improvements in measurement accuracy and efficiency.

The Panel discussed several generic instrumental design concepts; several viable choices are available. It also seems likely that one design could support both the ground-based and airborne programs. We offer the following additional comments:

a. It will probably be appropriate to break the wavelength coverage at about 5 to 6 μm. Design considerations will be different in the two wavelength domains.

b. Highly accurate radiometry will require the use of filters for spectral isolation. Use of a dispersing instrument for this part of the measurements, while very efficient, probably entails too many additional sources of error.

c. Spectroradiometry using adjacent square passbands is subject to error due to undersampling of the spectrum.

One aspect of the instrumental development is problematical. This is the specification and procurement of suitable arrays. It has been the experience of academic astronomers that such advanced high-tech devices are difficult for them to obtain, presumably because all the competent fabricators are already fully committed to defense programs. The feeling is that if procurement of the arrays is put in their hands it will create an unpredictable cost and schedule risk. It has been suggested that it might be more cost- and schedule-effective for the arrays to be supplied via an existing program such as the CE project.

3.4 GROUND-BASED OBSERVATIONS

The observing strategy will be designed to minimize systematic errors. Each of the stars will be observed several times in order to eliminate any observations made on nights when the atmosphere was not suited to spectroradiometry. Repeated observations will also find any stars that are variable and will insure that there are no residual systematic effects over the sky. A substantial subset of the stars will be measured at independent observatories in order to further reduce systematic errors. These intercomparison data will be analyzed by an independent organization in time to avoid propagation of error throughout the catalog.

We estimate the total time required to complete the ground-based portion of the program at about forty-eight nights, including extra time to accommodate overlap of observations and poor weather. This amount of time could be accommodated by two observatories over the planned two-year observing span without excessive impact on the existing research plans. However, this includes only minimal time for building up the supplemental catalog, thus underscoring the desirability of an ongoing program of observations.

3.5 SUPPLEMENTAL AIRBORNE PROGRAM

There are several spectral regions that are inaccessible from the ground. Data in these atmospheric blocking regions are relatively scarce and of variable quality. Additional, high-quality data in these regions could be acquired using the Kuiper Airborne Observatory (KAO) which is available to U.S. astronomers. After a large number of suitable stars has been characterized from the ground, we would begin the airborne portion of the program. During this stage the stars need be observed only once, minimizing the extent of the airborne operations. There will be an overlap in wavelength coverage between the airborne and ground-based programs so that systematic effects can be eliminated. The largest uncertainties will occur at wavelengths longwards of about 20 μm. We estimate that ten flights would be sufficient to allow the KAO data to be the sole source of spectral data in the blocking bands.

If airborne data are not available, the data set would be of potentially lesser utility, but would still be usable. In place of the KAO data there are archival data on a few stars and data from the Dutch Additional Experiment — a piggyback experiment on IRAS — on most stars. In addition, stellar atmospheres are well enough understood that a fairly good model spectrum can be constructed. Lack of KAO data would thus mean poorer quality of spectral data in the atmospheric blocking bands, but not complete absence of data. The effect of this problem on the user's synthetic in-band radiance values would depend upon not only the error in the spectral data but also the amount of structure in the user's passbands and the overlap of those passbands with the atmospheric blocking bands. For many programs there would not be a significant problem.

3.6 THE Q-PROBLEM

The number of suitable stars within the desired brightness range at 10 μm (*N*-band) and 20 μm (*Q*-band) is a critical question in determining the feasibility of an improved standard network. For $\lambda > 10$ μm the number of stars will be limited by nature rather than by questions of practicability, since the requirements for brightness and the data quality longwards of 10 μm tend to be mutually exclusive. To achieve a firm understanding of this situation, we found it necessary to draw up a specific list of possible standard stars (see Appendix E). Over the entire sky we find 48 stars that are brighter than magnitude 0 at N and Q and are neither variable nor are likely to have spectral features that would complicate synthesis of passbands from a limited suite of measurements. Nine of these stars are in the current standard network. With a slight relaxation on the requirements for nonvariability and well-behaved spectra, there are 38 stars brighter than magnitude −1. One of these stars is in the current network.

To deal with this problem, the brightest stars that meet all the listed requirements for data quality will be chosen to form the star network. The result will be a network that has fewer than the desired number of stars, many of which are too faint to provide excellent SNR. Supplemental catalogs will then be created in order to include a sufficient number of stars and stars of sufficient brightness. Brighter supplemental standards can be established using very bright, variable infrared stars; we estimate that inclusion of these objects will increase the number of reference stars to about 100 objects brighter than magnitude −3. These stars have time scales for variability of ~200 to ~2000 days, and their behavior repeats reasonably closely from cycle to cycle. Although it is not possible to use archival measurements to predict the irradiance of one of these stars with adequate accuracy, a combination of archival data and an approximately contemporaneous measurement (within ~ 1 week) would suffice. It is essential that the nonvariable standard network be established in order to implement this plan, since it is required for accurate observation of the supplemental stars.

4. RECOMMENDATIONS

4.1 DEVELOPMENT OF THE ASTRONOMICAL REFERENCE CATALOG

The Panel believes that the Astronomical Reference Catalog would be of sufficient value to justify proceeding with the project as outlined in this report. A listing of the tasks involved in creating the catalog is given in Appendix A. Schedule and cost estimates are also given. We recommend that the instrumental development and the ground-based observing program be closely coupled to allow most efficient interface between these tasks. Early involvement of academic astronomers would help avoid potential interface problems. Comments on the significant risks follow.

4.1.1 Instrumentation

Design and fabrication of the appropriate instruments entail the largest schedule and cost risks. In addition, startup for the instrumentation begins the project critical path. Cost could be reduced by replacing the parallel approach with a primary-observatory and secondary-check task.

4.1.2 Ground-Based Measurements

Ground-Based measurements entail the largest technical risk, which is felt to be low. Because cost is driven by the number of star observations required, changing to a primary observatory approach will not produce any savings in this task. Further, many observatories might be unwilling to dedicate as much time to this project as one observatory would need to do.

4.1.3 Archival Research

Archival research could provide some benefit by itself with a small documentation effort.

4.1.4 Airborne Measurements

The full set of airborne measurements is a desideratum designed to guarantee adequate high-quality spectral data in the absence of any other data in the atmospheric blocking bands. The impact of a shortfall in this task cannot be addressed until the relevant part of the archival research is complete. The KAO management may be able to give a more favorable response when we can be more specific about objectives and schedule.

4.2 ONGOING PROGRAM

Although it is not directly required in establishing the Astronomical Reference Catalog, a continuing program of supporting observations would be very useful. Such a program would utilize the equipment developed by the ARC program to make occasional measurements of selected stars. Because the measurements could be made differentially with respect to the ARC, significant quantities of high-quality data could be obtained at a relatively low level of effort.

The continuing measurement program would support two goals. First, these observations would allow the catalog to be continually expanded, thus providing better support to all programs. Second, the continuing observation program would allow use of variable stars or of stars fortuitously observed in a particular program but not previously characterized. The utility of such observations is emphasized by the fact that at least one current defense program has already arranged for similar (though not as precise or timely) observational support.

4.3 CALIBRATION GROWTH

An attractive feature of the proposed ARC is its capacity to incorporate future improvements in the absolute calibration and the facilitation of those improvements.

4.3.1 Relative and Absolute Measurements

The observations used to construct the ARC will be relative measurements. Such measurements are generally easier to perform than absolute measurements, as is reflected in the accuracy values shown in Figures 2-1 and 2-2. We have presented the catalog as if it were a compilation of measurements of irradiance relative to α Bootis. Equivalently, it may be thought of as defining a set of virtual copies of α Bootis spread over the sky. In this view the relative accuracy reflects how well an individual star represents the mean of all the stars in the catalog; the absolute accuracy reflects how well the mean of all the stars in the catalog represents physical reality. Once the catalog is established by precise relative measurements, any sufficiently accurate calibration measurement of any of the stars can be used to improve the absolute accuracy of the catalog.

4.3.2 New Observations

In order to fully contribute to improving the catalog's absolute calibration, new measurements will have to be independent of previous calibration experiments. This effectively rules out further work based on model stellar atmospheres and further measurements of catalog stars with respect to existing calibration standards. At least two such new experiments are plausible. The effort to coordinate such experiments between the agencies involved should prove to be worthwhile.

Ground-, air-, or space-based differential measurements of instrumented calibration spheres and one (or preferably more) catalog star could offer a large quantity of well-controlled calibration data. The instrumented calibration spheres could be either rocket-launched or balloon-borne. The fact that any of the stars in the catalog could be selected for such an experiment will minimize the uncertainties in any needed correction for atmospheric transmission.

Future planetary space probes can be expected to provide a wealth of detailed data on such objects as asteroids and the Jovian satellites. Models based on these data should provide useful calibration objects at least for limited periods of time. Again, the fact that any of the catalog stars could be selected for comparison will minimize atmospheric transmission error.

APPENDIX A
THE ASTRONOMICAL REFERENCE CATALOG PROJECT

A.1 STATEMENT OF WORK

Development of the Astronomical Reference Catalog (ARC) consists of eight tasks. These tasks are listed and briefly defined below.

A.1.1 Instrumentation

Instrumentation includes the construction of dewar and data processor. It is anticipated that the best results would be achieved by supplying the detector arrays as customer furnished equipment (see Section 3.3).

A.1.2 Ground-Based Measurements

A program for ground-based measurements is carried out at one or more research observatories. The instrument to be used would be left in the care of the observatory.

A.1.3 Archival Research

A search of archival data is made to support the definition of airborne data requirements, the selection of candidate stars, and the collation of usable data.

A.1.4 Airborne Measurements

A program of airborne spectroscopic measurement is developed.

A.1.5 Data Integration

Data integration inlcudes the compilation, assessment, and integration of data from various sources.

A.1.6 Documentation

Documentation consists of the preparation of data description and user's manual.

A.1.7 Project Management

The project is managed by utilizing project oversight, task integration, and sponsor reporting.

A.1.8 Ongoing Support

A long-term, low level of effort observation program is designed to support the use of supplemental stars, additions to the catalog, and future calibration experiments.

A.2 SCHEDULE ESTIMATE

Figure A-1 summarizes the project schedule.

A.3 ESTIMATE OF COST AND STAFFING

Table A-1 lists estimated costs and staffing requirements.

TABLE A-1

Estimate of Cost and Staffing

	PROJECT TOTALS ($M)
Instrumentation (not including arrays)	
Total for two complete similar instruments	1.0
Ground-Based Measurements (parallel approach)	
Facilities support plus four astronomer-years*	1.0
Archival Research	
Two astronomer-years	0.3
Airborne Measurements (assumes five flights)	
Facilities support plus one astronomer-year	0.5
Data Integration	
Two Research and Development staff-years	0.5
Documentation	
One Research and Development staff-year	0.3
Program Management	
Two Research and Development staff-years	0.5
	4.1
Ongoing Support Observations	$50,000/yr

* Astronomer-year: one person-year of effort by a mixture of research faculty members and graduate students.

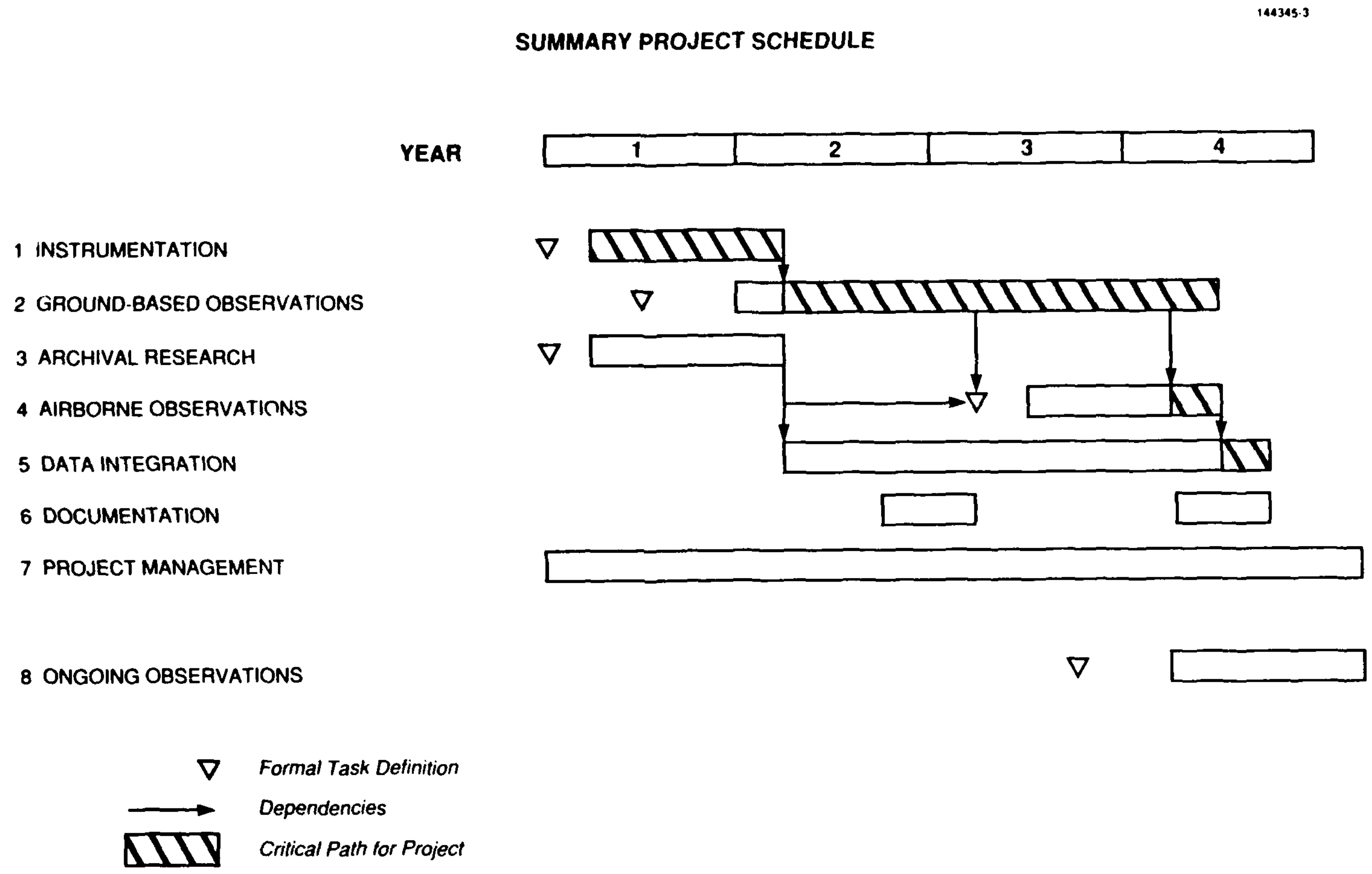

Figure A-1. Summary project schedule.

APPENDIX B
IR CALIBRATION

B.1 OVERVIEW

A calibration of the raw instrumental signals in terms of physical units is required for most interpretations of astronomical observations. This is particularly true for measurements of nonstellar sources, where there may be significant deviations from the well-defined family of roughly blackbody spectra that characterize stars. Consequently, calibration is of critical importance in the IR regime, where nonstellar sources or IR excess emission from stars are the usual targets. The process of absolute calibration consists of a series of steps, each of which will be treated in turn:

a. Measure absolute fluxes, corrected for atmospheric extinction, for selected celestial objects. Such measurements are arduous, and hence are usually only obtained at a limited set of wavelengths and for a few objects.

b. Transfer absolute fluxes to objects suitable for routine observation, i.e., establish a network of nonvariable standard stars with a wide distribution on the sky and with appropriate brightnesses.

c. Determine the relative spectra of the standard stars with sufficient accuracy to allow extension of the calibration to any user passband.

B.2 ABSOLUTE MEASUREMENTS OF SELECTED OBJECTS

B.2.1 Direct Calibration

The most straightforward method to absolute calibration would be to measure a laboratory reference blackbody source and a suitable celestial source with the same instrumentation. The superficial simplicity of this scheme is not achieved in practice because of the large dynamic range between the fluxes from suitable laboratory sources and the fluxes from the much fainter celestial objects. Nonetheless, satisfactory results have been reported between 1 and 5 μm by Blackwell et al. [1] and Mountain et al. [2]. A similar experiment at 11 μm is described by Rieke et al. [3].

An alternate technique utilizes the radiometers on spacecraft. These instruments are used to observe a planetary object, which can be measured simultaneously with an earth-based telescope along with suitable standard stars. This sequence transfers the laboratory calibration of the radiometer to the standard star. The most successful application of this technique is described by Rieke et al. [3], using measurements of Mars by instruments on the Viking Orbiter. Table B-1 shows the calibrations achieved in these experiments. As in most of the original accounts, the calibration is expressed as the flux of the A0 star Vega at the wavelength in question.

TABLE B-1

Absolute IR Calibration Expressed as Flux of Vega

Wavelength (μm)	Direct Transfer (Jy)	Solar Analog (Jy)	Average (Jy)
10	41.3 ± 3.3[3]	41.7 ± 3.0[3]	
	40.0 ± 1.3[3]	42.6 ± 1.3[5]*	
	40.2 ± 1.2	42.4 ± 1.2	41.3 ± 0.9
4.8	178 ± 12[2]	168 ± 8[4]	171 ± 7
3.54	287 ± 8[1]	279 ± 8[4]	283 ± 6
2.22	666 ± 20[1]	644 ± 20[4]	655 ± 14
1.60	—	1055 ± 32[4]	1055 ± 32
1.26	1531 ± 46[1]	1622 ± 49[4]	1574 ± 34

* Calculated from IRAS data summarized by Waters et al. [5]

B.2.2 Solar Analog Method

A second method, originally suggested by Harold Johnson, uses stars of similar spectral type to that of the sun. The absolute spectrum of the sun has been measured in considerable detail; if it is assumed that all solar-type stars have identical spectral distributions, their absolute flux as a function of wavelength can be obtained by normalizing according to the relative brightnesses of the stars and the sun at a single wavelength. Here, the dynamic range problem occurs in the step of referring the brightness of the sun to that of other solar-type stars, which are typically 10^{12} times fainter. Nonetheless, such measurements are available, and calibrations based on this approach are reported by Campins et al. [4] at 1 to 5 μm and Rieke et al. [3] at 10 μm. These references summarize previous work along the same lines. The resulting measurements are listed in Table B-1. An additional accurate calibration can be derived from the measurements at 12 μm of solar-type stars by IRAS, as summarized by Waters et al. [5]. In this case, the measurement of an individual solar-type star is of limited accuracy, but a large number of such stars compensates, and an overall accuracy of about two percent in the visible-to-10-μm ratio can be achieved.

Campins et al. [4] find evidence for variations on the order of two percent in the visible-to-IR colors of nominally identical solar-type stars. This scatter is one of the fundamental limitations in the solar-analog calibration; nonetheless, the accuracies achieved appear to be similar to those from direct transfer of calibrated sources.

The agreement between the two calibration methods is extremely good. It is shown more clearly in Figure B-1, which compares the individual methods and estimated errors with the weighted average (last column in Table B-1). Not only do the calibrations agree within the estimated errors, but there is no discernable trend in the discrepancies.

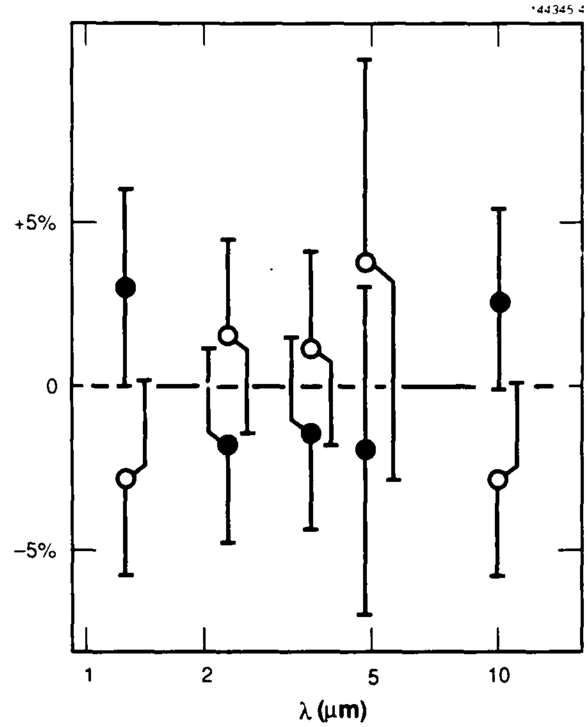

Figure B-1. Comparison of direct and solar analog calibration.

B.2.3 Methods for Long Wavelengths

Longward of 10 μm, the situation for absolute calibration is worse, mostly because of the difficulty in making accurate measurements through the poorly transmitting atmospheric window. The best procedure is probably to extrapolate the calibration from 10 μm using solar-type stars or some other stellar type with a well-understood atmospheric model. The IRAS data should allow checking the accuracy of these estimates. There is the potential in some years to use the IR radiometer on Galileo to measure Jovian satellites at 20 μm, allowing with suitable ground-based measurements, a transfer of its calibration to standard stars.

A competing technique at 20 μm is to use models of asteroids for extrapolation. Longward of 20 μm, such models are to be preferred because the strong shorter wavelength emission by stars makes extreme demands on the blocking of filter leaks. To achieve calibration on stars at 100 to 200 μm [assuming a platform with sufficient sensitivity such as ISO, the Infrared Space Observatory planned by The European Space Agency (ESA), or The Space Infrared Telescope Facility (SIRTF), the U.S. cryogenic telescope planned by NASA], short wavelength filter leaks would need to be blocked to 1 part in 10^8.

The current status of asteroid models is shown in Figure B-2, kindly communicated to us by L.A. Lebofsky. This figure compares the asteroid diameters deduced at three IRAS spectral bands: B1 (12 μm), B2 (25 μm), and B3 (60 μm). The IRAS band 1 calibration is based on the work of Rieke et al. [3] and should have an accuracy of about three percent. Figure B-2 shows that the model diameters at 25 and 60 μm tend to be larger than those at 12 μm by as much as ten percent. Since the flux varies as the square of the diameter, this effect could arise from an error of as much as twenty percent in the IRAS calibration. Alternately, some or all of the discrepancies could come from inaccuracies in the models.

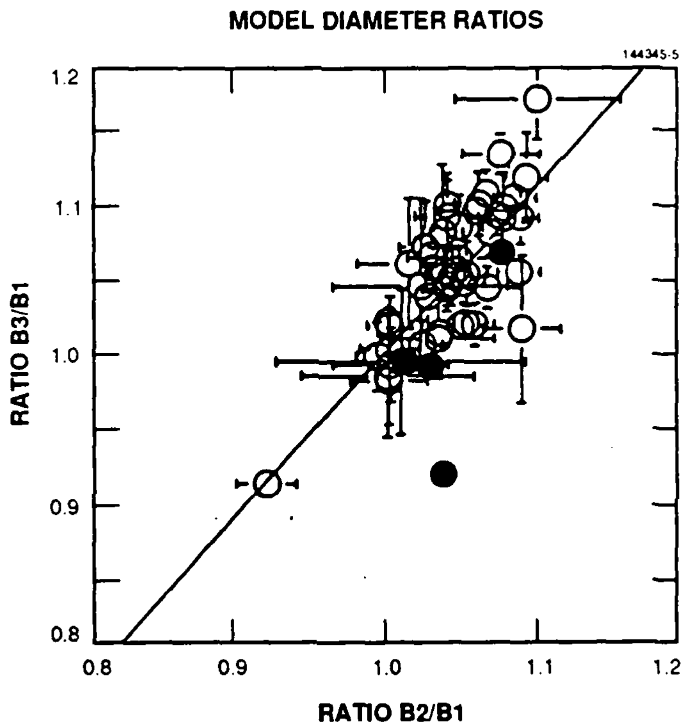

Figure B-2. Comparison of asteroid model diameters.

B.3 TRANSFER TO A NETWORK OF STANDARD STARS

The most widely used list of standard stars for the near-IR is described by Elias et al. [6]. Unfortunately, this network is less thoroughly cross-calibrated with primary calibration stars than would be desirable, leading to an additional source of error in the calibration of measurements. Note that the magnitude scale of these authors assumes that Vega is at zero magnitude, whereas most optical scales, and many IR scales, place Vega slightly positive, magnitude +0.02 in the IR.

A set of standard stars for 10 and 20 μm is listed by Rieke et al. [3]. The relative magnitudes appear to agree with the IRAS data (Beichman et al. [7]). This scale takes Vega to be at a magnitude of +0.02.

In both wavelength ranges, the most desirable addition would be to extend the system of well-calibrated stars to have many more members. This effort is rather onerous with single-detector-aperture photometers, particularly at 10 and 20 μm, where small apertures must be used to achieve good sensitivity, but the repeatability then suffers from centering errors. IRAS data would be useful as a beginning, but it is likely that the relatively few passes over each star and the irregularities in the IRAS beam profiles would preclude achieving the necessary accuracy by this means alone. A very promising approach would be to use array detectors to extend the standard systems.

At 10 and particularly 20 μm, standard star networks selected to have only members with no variability and well-behaved spectra may be too faint for accurate observation by instrumentation that is less than state-of-the-art in sensitivity. Although there are brighter stars, most are now known to be long-period, irregular variables; others are excluded from the list because their spectral types imply that they may have variability or IR spectral features due to circumstellar shells. Because the phase of irregular variables cannot be predicted with certainty, such stars are not really suitable as standards; where high accuracy is required with instruments that cannot use the well-established set of standards, it may be necessary to carry out simultaneous transfers from the bright stars to the standards with a second, more sensitive instrument.

B.4 DETERMINE SPECTRAL CHARACTERISTICS OF STANDARD NETWORK

One possibility for a network of standards with predictable spectra is suggested by the success of the solar-analog calibration. If solar-type stars are used, the solar spectrum (Labs and Neckel [8]; Neckel and Labs [9]) can be used to interpolate and determine the response of a system with any spectral passband. Campins et al. [4] show that the IR colors of solar-type stars are not a strong function of the exact match of the star to the sun, and late F and early G dwarf stars are common; thus, a large number of suitable spectral calibrators are available. Unfortunately, none of the widely used lists of standards, including that of Elias et al. [6], has a significant number of solar-type stars.

The similarity of the IR spectra of A stars (Leggett et al. [10]) suggests that they can also be used as spectral standards. Here, the difficulty is the disagreement of model atmospheres with the measured calibration. Mountain et al. [2] give an empirical correction. However, until the cause of this discrepancy is understood and better atmospheric models are available, there is clearly some risk in applying it.

The IRAS data show wide dispersions for the IR colors of B, A, and M stars, but very tight ones for G and K stars (Waters et al. [5]). This result would suggest that G and K stars might be the most satisfactory spectral calibrators and that a program to measure the IR spectra of K stars would therefore be useful.

APPENDIX C
SPATIAL EXTENT REQUIREMENT

In setting a requirement on spatial extent (or subtense) of stars in the catalog, there are four issues that must be addressed.

a. What is the effect of object extent on the radiometry performed both in setting up the catalog and in using it?

b. What size blur circle will characterize the sensors of the future?

c. What spatial resolution is attainable from ground-based measurements?

d. What is the range of spatial extent of the stars that will be in the catalog?

We will examine these issues and then define the specification for measurement of spatial extent. Several of the effects discussed are wavelength dependent. Rather than discussing all the spatial extent issues as functions of wavelength, we will choose as a typical wavelength 11 μm — approximately the center of the midwave atmospheric transmission band. For several reasons errors due to uncorrected finite object extent will be most troublesome in this wavelength region. At longer wavelengths diffraction increasingly overwhelms the real size of physical sources. In addition, the accuracy requirement loosens with increasing wavelength. At shorter wavelengths the nature of the stars chosen for the catalog is such that finite extent need not be an issue. This point will be discussed further in Section C.4.

C.1 EFFECT ON RADIOMETRY

C.1.1 Measurements Used to Create the Catalog

Although loss of energy in the image "wings" can be a problem, it is quite easy to avoid this problem. In particular, since radiometry will probably be performed using an array of detectors, integration of the power in the entire image will be straightforward. There will be a loss of SNR for extended objects, but since all the proposed objects are quite bright this is not a problem.

C.1.2 Measurements by the User

The user will not be making spatially resolved measurements but will instead be analyzing the focal plane data using an assumed image profile. The image profile ordinarily is calculated assuming zero extent of the star. Ideally, then violation of this assumption must be small enough that it does not lead to excessive error — say one percent as a limit. An alternative would be to customize the profile to account for a given object extent, thus correcting for the extent up to some maximum correction that leaves a residual error no greater than the limit previously set. To some extent, this process would be antithetical to the concept of calibration using stars but would be a way of allowing use of otherwise unusable reference stars.

We can get a quantitative idea of the effect of object extent on radiometry using the following simple model. Suppose that the nominal blur circle is described by a Gaussian distribution and that the detector size is matched to this by requiring that 80 percent of the incident power fall on the detector centered on the distribution. This approximates common engineering practice. Suppose also that the object may be described by a Gaussian distribution with a distribution parameter some percentage of the nominal blur circle.

What falls on the detector is then a composite spot described by a Gaussian distribution with an extent equal to the root-sum-square of the nominal blur and the object extent. This composite spot will put less power on the detector. The power loss for several values of the object extent are listed below.

Source extent as percent of nominal blur (percent)	Composite spot size compared to nominal blur	Power loss (percent)
0	1.000	0.0
10	1.005	0.4
20	1.020	1.5
30	1.044	3.5
40	1.077	6.1
50	1.118	9.2
60	1.166	13.0
80	1.281	21.2

The above analysis assumes a static measurement of the blurred image centered on a detector, perhaps with chopping to remove dark-current effects. A more complex scanned array with spatial filtering would be somewhat less sensitive to blur growth. With two columns of detectors (one offset with respect to the other by half a detector spacing) and with two-dimensional matched filtering of the multiple detector outputs, the effective "power loss" would be approximately 65 percent of the values tabulated above, allowing the use of stars having somewhat larger subtense. For this discussion, however, we will be conservative and use the values from the table. According to this table, we could meet the one percent error requirement by limiting stars to those having subtense less than about fifteen percent of the blur size. If corrections up to ten percent were considered acceptable, then stars with subtense up to about fifty percent of the blur size could be used.

C.2 EXPECTED SIZE OF NOMINAL BLUR CIRCLE

The blur circle for a sensor (more properly the point spread function for the system — including any atmosphere) is a composite of many effects, including diffraction, aberration, fabrication error, alignment and defocus error, atmospheric blurring, and line-of-sight (LOS) jitter. Projecting the likely minimum blur circle for sensors in the next few decades is somewhat speculative. However, we can get some idea of the limits imposed by nature and practicality by considering the various contributors in turn. First, let us assume that at least some sensors will operate in space. In that case, atmospheric effects will not contribute and line-of-sight jitter will be negligible. Alignment and defocus can be actively compensated by using a sufficiently elaborate design; we shall assume it will be compensated.

The remaining three sources of blur must be traded off to reach some optimum compromise. At 11-μm wavelength a 1-m aperture will produce a diffraction disk about 27 μrad in diameter. Experience suggests that a telescope of this size can readily be made diffraction-limited in this wavelength range — i.e., other sources of blur are negligible compared to diffraction. As the diameter of the aperture increases, the diameter of the diffraction disk decreases, and it becomes increasingly difficult to achieve diffraction-limited performance.

A major driver to telescope performance is the size of the field-of-view (FOV). It is assumed that defense-related sensors will need FOVs at least 2 deg in radius. As an example of the problems raised by this, consider the Hubble Space Telescope. This telescope has a diameter of 2.4 m and is intended for use in the visible region of the spectrum. To take advantage of the high potential performance of a 2.4-m space-borne telescope, a relatively sophisticated optical design was used. This design eliminates most third-order aberrations, leaving only a modest third-order astigmatism amounting to 1.5 μrad at the edge of the 14 arc min FOV. Presumably this design choice represents some sort of optimum trade-off between correction and fabricability for a telescope of this size. Within the FOV the astigmatism increases with the square of the distance from the field center. Extrapolating this behavior out to the 2-deg field radius gives an astigmatic blur of 110 μrad.

It is possible to design even more highly corrected optical systems that would be able to hold the aberration to a low value over a larger FOV, but the fabrication then becomes problematical. Fabrication error is unfortunately the error least amenable to cure by expenditure of money. Considering this trade-off and considering that we have assumed that alignment and defocus blur will not contribute, it seems at least plausible to predict that no defense-related system with a blur circle less than 25 μrad will be fielded. Incorporating the conservative fifteen percent limit derived above, we are lead to a limit on star subtense of 4 μrad to guarantee a radiometric error of less than one percent.

C.3 RESOLUTION OF GROUND-BASED MEASUREMENTS

The resolution attainable by a ground-based sensor will be determined by choice of telescope and detector size, over which we have some control, and by atmospheric blurring, over which we will have no control.

C.3.1 Atmospheric Blurring

Whatever the true extent of the source being measured, the radiation will arrive at the telescope aperture distorted by atmospheric effects. There, its apparent extent will be described by the convolution of the true extent and the atmospheric Point Spread Function (PSF). If we knew the PSF well enough and achieved sufficient SNR in our measurement, we could expect to do a reasonable job of reconstructing the true source image. (But see caveat below.) Unfortunately the PSF is neither simply described by just one parameter, nor is it independent of LOS and time.

As a practical matter, the best we will be able to do is to measure the image of a known point source as near as possible in direction and time to the program object. If the image of the program object differs from that of the point source, we attribute the difference to the nonpoint-source nature of the program object. Because of the great uncertainty in our knowledge of the PSF, any analysis more elaborate than a one-parameter description of the blurring is not justified. In this case, we then simply take the root-square difference as defining the extent of the program object. With such a naive analysis and such large uncertainties, we cannot be confident of any results smaller than the size of the atmospheric blur circle.

Astronomers have accumulated a large body of statistics on the atmospheric PSF in the form of "seeing" estimates. The seeing is defined as the diameter (as if there were a hard edge) of an average visible image of a star in the absence of diffraction. At good sites arc-second seeing is not uncommon, with subarc-second seeing as the prize awaiting a persistent observer. Attempts to quantify seeing further yield commensurate and self-consistent results, but serve also to emphasize that atmospheric blurring is much too complicated a phenomenon to be adequately described with just one number. Limited experience in the IR indicates that seeing at 11 μm is smaller than in the visible by a factor of almost two. We thus anticipate occasional IR blur circles as small as 2 to 3 μrad and can thus expect a specification of 4 μrad to result in a practicable observing program.

C.3.2 Instrumental Effects

The 4-μrad limit on object extent combined with the 4-μrad limit on acceptable seeing leads to a requirement that the instrument be capable of reliable measurements of 6-μrad blur circles. This requirement in turn imposes limits on detector size and on acceptable diffraction.

The 88-in telescope belonging to the University of Hawaii at its Mauna Kea Observatory is typical of the telescopes likely to be available for the ARC program. For this telescope at an 11-μm wavelength, the diameter of the diffraction disk is about 12 μrad. Here we have a situation similar to the atmospheric blurring case, but with a crucial difference. Unlike the atmospheric PSF, the diffraction pattern is well known and stable. In the presence of sufficiently high SNR (but see caveat below) it is reasonable to expect to be able to reconstruct the atmospherically blurred image reliably to a resolution approaching the data-sampling resolution.

C.3.3 The Caveat

The discussion of measurement has thus far been rather oversimplified. In fact, we are not trying merely to detect or measure the total flux from the object but are trying to measure the two-dimensional distribution of the flux at the focal plane. This fact introduces some additional complications that, while not affecting the numbers derived above, must be considered in evaluating a proposed measurement technique. It is helpful to move the discussion to the Fourier domain, where we will be concerned with the two-dimensional Fourier transforms of the images and of the PSF. This latter is also known as the Modulation Transfer Function (MTF).

First consider the question of SNR. The Fourier transform of the radiation pattern at the focal plane is the product of the Fourier transform of the unblurred source and the atmospheric MTF. Restricting "signal" to mean information about the geometry we are trying to measure, we can see that the SNR is a function of spatial frequency. When the MTF becomes very small, as it does at high spatial frequency, the SNR will also become small, and the corresponding geometric data will be "lost in the noise." The information about the fine detail is thus effectively destroyed by the atmospheric blurring.

Next we note that the process of imaging on an array of detectors has an MTF that has an effective cutoff frequency that is higher for smaller detectors. It would be inefficient to use such small detectors that the imaging MTF remained high at frequencies where there was no signal passed by the atmospheric MTF. On the other hand, it is not safe to let the detectors be so large that the imaging MTF is small at frequencies where there is still significant geometric information, because that information will be aliased giving rise to a falsified image. It is possible that it would be convenient to add a small amount of defocus to dilute the effect of variable atmospheric seeing.

C.4 STARS

The primary candidates for inclusion in the catalog are so-called normal stars — dwarfs and giants but not supergiants. These stars are essentially hard-edged objects, and none has a subtense as seen from the earth as big as 1 μrad. In the 2 to 8-μm wavelength range we will be able to choose normal stars, and thus do not expect finite object extent ever to be an issue. At longer wavelengths, however, we will increasingly need to include stars that are not normal. Objects that are very bright in the IR, especially at the longer wavelengths needed in this program, are likely to be supergiant stars with extended envelopes, clusters of stars, or stars embedded in galactic molecular clouds. Many of these will show excessive extent, requiring that the user correct for the extent or that they be rejected from the catalog. A few normal stars are surrounded by disks, shells, or clouds of dust that radiate in the IR. For instance, α Lyr was discovered to be surrounded by a shell of dust with an apparent diameter of 100 μrad in the 60-μm IRAS band. Because of its low temperature, the shell is not detectable in the 12-μm band.

Because intensity falls off so rapidly on the short wavelength side of the blackbody function, we can limit our concern to shells at temperatures of at least 263 K — the temperature that has its peak radiation at 11 μm. The dust will be in thermal equilibrium with the radiation from the central star, so we can calculate the temperature as a function of star brightness and distance from the star. The best candidates for catalog standards are K-type giants — stars about 100 times as bright as the sun.

For such a star, the equilibrium temperature falls to 263 K at a distance of 11.2 Astronomical Unit from the star. The nearest K-type giant, β Gem, is at a distance of about 11 pc. If β Gem actually had a dust shell as warm as 263 K, its apparent extent would be just under 5 μrad. The central star also radiates at 11 μm, so the marginal error due to the hypothetical shell would be further diluted by the point-source radiation of the star itself. Thus, we do not expect extent to be an issue for the normal stars. Of course, a small fraction of the candidate stars may turn out to be abnormal and will have to be rejected.

Irregular extended objects such as molecular clouds or star clusters will probably have to be rejected even from the supplementary catalog. We are, therefore, most interested in stars surrounded by dust shells. As we have already seen, at 11 μm we do not expect to see many cases of normal stars with dust shells large enough to affect the radiometric accuracy. However, the apparent size of a dust cloud would depend on the wavelength if it was optically thin (the usual case). The dependency is $r \sim \lambda^2$, so that significant extent at 22 μm is much more likely. This larger subtense can, of course, be detected, but we may not have the freedom to reject all such stars. Fortunately, the increasing size of the diffraction disk partially compensates for the larger source subtense at longer wavelengths. In the case of shorter wavelengths, the λ^2 dependency leads to very small apparent sizes for dust clouds. We will not be concerned with their presence, nor will we be able to measure their subtense. We will, however, be able to detect their presence from a measured IR excess in the spectrum of the source.

C.5 SPECIFICATION

Let us summarize the important conclusions discussed above.

a. The sensor most sensitive to finite object extent will have a blur circle and detector spacing of 25 µrad.

b. For object extent less than 4 µrad, we are guaranteed that the radiometric error due to finite extent will be less than one percent.

c. It is plausible that for object extent greater than 4 µrad but less than (say) 15 µrad, there will be a radiometric error that is greater than one percent but that is correctable to a residual error of less than one percent.

d. A 4-µrad threshold for detection of finite extent is regularly achievable at a good astronomical site using a telescope aperture of 2 to 3 m.

e. For stars, the presence of a dust shell will lead to both finite subtense and spectral IR excess. The subtense may be a function of the wavelength.

Based on these conclusions, we propose the following data set specification for spatial extent.

C.5.1 Primary Catalog

No object in the primary catalog shall have a spatial extent at 11 µm in excess of 4 µrad. Stars without measurable subtense but with IR excess will be retained only if needed and will be flagged.

C.5.2 Supplementary Catalog

Objects in the supplementary catalog may have a spatial extent greater than 4 µrad if a correction factor may be calculated that allows a nominal measurement (defined below) to be corrected to a residual error of less than two percent. An estimate of the residual error shall be provided.

The nominal measurement consists of scanning the test object across a 25-µrad slit and sampling every 8 µrad. The result of the measurement is to be the power estimate produced by a filter matched to an identical scan of a point source.

C.5.3 Imaging Wavelengths

Assessment of object subtense should be performed in passbands at about 5, 11, and 22 µm.

APPENDIX D
SPECTRAL RESOLUTION

In order to utilize stellar measurements, the user will need to calculate values of

$$Y_a = \int \Phi(\lambda)\, R_a(\lambda)\, d\lambda \tag{D.1}$$

where $\Phi(\lambda)$ is the spectral irradiance and $Ra(\lambda)$ is a particular user passband or response profile. The spectral irradiance will, however, be known only as a finite set of point values $\Phi(\lambda_i)$, so the user will actually calculate

$$Y'_a = \sum \Phi'(\lambda_i)\, R_a(\lambda_i)\, \Delta\lambda \tag{D.2}$$

The difference between Y and Y' is the error due to loss of information associated with finite resolution in the data set $\Phi(\lambda_i)$. Obviously, the more closely spaced the λ_i are (high resolution), the less the error due to loss of information will be.

We may characterize the error more quantitatively by generalizing Equation D.1 to

$$Y(\lambda') = \int \Phi(\lambda)\, R(\lambda' - \lambda)\, d\lambda \tag{D.3}$$

where we reconstruct the specific passband values by setting λ' to the central wavelengths of the user passbands. If we now take the Fourier transforms of Y, Φ, and R we can write:

$$y(s) = \phi(s)\, r(s) \tag{D.4}$$

where the lowercase symbols are the transformed functions, and s is the Fourier variable, which in this case measures the structural detail in the spectrum and response profile. For example, the average value of $R(\lambda)$ is represented by $r(s)$ at $s = 0$, whereas the highly detailed (very wiggly) part of $\Phi(\lambda)$ is represented by $\phi(s)$ at high values of s. The dimension of s is cycles per range of wavelength.

The version of Equation D.4 corresponding to Equation D.2 is

$$y'(s) = \phi(s)\, r(s) \tag{D.5}$$

where $\phi'(s)$ is given by

$$\phi'(s) = \begin{cases} \phi(s) & s \le s_c \\ 0 & s > s_c \end{cases} \tag{D.6}$$

The information loss is specified by the cutoff s_c, above which the actual spectrum is replaced by zero. The resolution specification will come about as follows. There is a maximum error we will accept in the synthesis of in-band irradiance, and thus a maximum information loss that can be tolerated. This leads to a minimum value of the cutoff and thus a minimum resolution.

To avoid error, we wish to have $y'(s)$ as close as practicable to $y(s)$. Now if $\phi(s)$ is actually very small above some value of s, then we can choose that as the cutoff and replace the small values of ϕ with zero without introducing any significant error. In fact, $\phi(s)$ does not always get very small at useful values of s. We will therefore make the very conservative assumption that ϕ remains high (of order unity) at all values of s and will set the cutoff on the basis of the properties of the response profile.

Figure D-1 shows a nominal idealized passband, similar in many respects to typical user passbands. In this plot, the independent variable is the dimensionless relative wavelength $x = \lambda/\lambda_c$. For example, at 12 µm the full width at half maximum would be 2.8 µm, and the cut-on interval would be 0.4 µm. This passband can be represented by the Fourier series

$$R(x-.876) = a_o + \sum a_n \cos 30\pi n(x-.876)/4$$

with

$$a_o = 0.875$$

$$a_n = 0.811 \left[(-1)^n \cos 3\pi n/4 - 1\right]/n^2$$

The coefficients a_n are the discrete equivalent of the Fourier transform. The squared coefficients are plotted in Figure D-2, with the ordinate plotted in decibels with respect to a_o. None of the user passbands we have looked at show more response at high frequencies than this plot, so we take the nominal passband to be the most stressing case. (We note that the transform is dominated by the term at $n = 0$, the "DC-term." This behavior is to be expected for a system using a square-law detector — to first order a measurement is of the λ-average flux in the neighborhood of λ_c.)

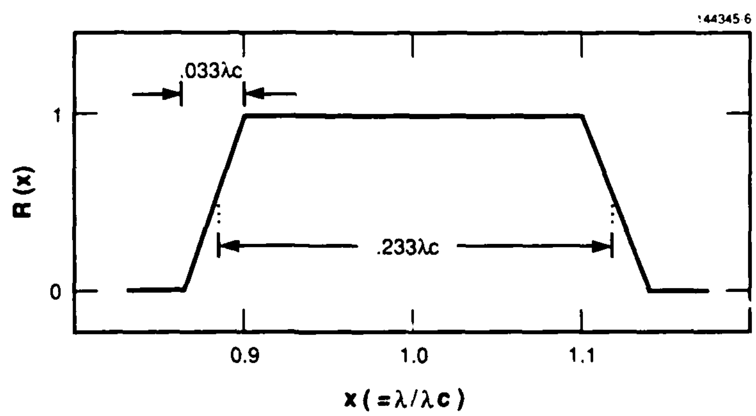

Figure D-1. The idealized nominal passband.

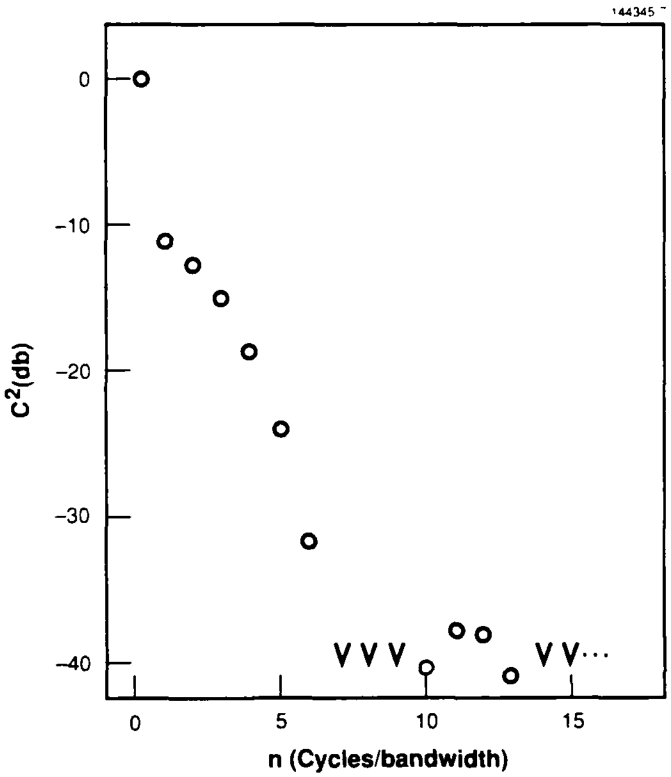

Figure D-2. Power spectrum of the nominal passband.

The –20-dB point on the "curve" is at about $n = 4.5$. This seems a reasonable choice of cutoff because contribution to y' above this point is limited to one percent of whatever part of $\phi(s)$ is nonzero above n = 4.5. We can now derive a specifcation on resolution. The cutoff value is 4.5 cycles in an extent of 0.266 λ_c or 1 cycle per 0.059 λ_c. To sample the component at $n = 4.5$ adequately, we need sample spacing close enough to give two samples per 0.059 λ_c — 2 $\Delta\lambda$ < 0.059 λ_c, or resolution $\lambda_c/\Delta\lambda \geq 34$. Since the assumption of unity $\phi(s)$ is a great overestimate of the detailed structure in stellar spectra, we feel comfortable relaxing the requirement to $\lambda/\Delta\lambda > 30$.

It is important to remember that the data set $\Phi'(\lambda_i)$ is NOT the set of monochromatic values of $\Phi(\lambda)$ evaluated at λ_i. Instead it is the set of values of a reduced-resolution spectrum, where the reduction is specified by requiring the Fourier transform to be as defined in Equation D.6.

A constant resolution implies sampling at wavelengths at constant-ratio spacing.

$$\frac{\lambda_{n+1}}{\lambda_n} = \frac{2\rho + 1}{2\rho - 1} = \eta , \tag{D.7}$$

where

$$\rho = \lambda / \Delta\lambda \quad .$$

For $\rho = 30$, $\eta = 1.033898305\ldots$

Although a data set tabulated at wavelengths defined by Equation D.7 may be readily produced (assuming the observational data support this specified resolution), it does make evaluation of Equation D.2 slightly awkward. We may ameliorate this situation by noting

$$\begin{aligned} Y'_a &= \sum \Phi'(\lambda_i)\, R_a(\lambda_i)\, \Delta\lambda_i \\ &= \sum \lambda_i\, \Phi'(\lambda_i)\, R_a(\lambda_i)\, (\Delta\lambda_i / \lambda_i) \\ &= \sum \lambda_i\, \Phi'(\lambda_i)\, R_a(\lambda_i) / \rho \end{aligned} \qquad \text{(D.8)}$$

If $\lambda_i \Phi(\lambda_i)$ tabulated quantity, Equation D.8 may be readily evaluated.

APPENDIX E
SELECTION OF A POSSIBLE STANDARD STAR NETWORK

E.1 INTRODUCTION

A set of stars used as calibration standards must be thoroughly intercompared so that the relationship between any pair is precisely defined and stable. Candidates for inclusion in such a stellar network should satisfy the following requirements:

a. They must be of a brightness that can be measured at high accuracy without danger of saturation.

b. They should be distributed well over the sky.

c. They should preferably be nonvariable. At least their brightnesses should be accurately predictable.

d. They should be point-like, so instruments with different FOVs will obtain the same calibration.

e. They should be at well-determined positions.

f. They should have similar spectral energy distributions, so that transfers from one standard to another will not need complex spectral modeling. This last is desirable, though not essential.

Some subsets of these requirements can be met by a variety of astronomical objects — e.g., stars, asteroids, compact nebulae. Stars are the most satisfactory solution in terms of meeting all of the requirements. Comparison of the IRAS data with visible photometry in Waters et al. [5] shows that the optical-to-infrared colors are particularly well behaved for stars of spectral types between A0 and K7. It is known from optical photometry that stars over this range of spectral type tend to be nonvariable, and stellar atmospheres are best understood over this range (particularly A through G types). Thus, the most satisfactory standard networks will be based on stars of types between A and K.

For the brightness ranges desired at various wavelengths, it is apparent that there is a more-than-adequate number of satisfactory stars for standard networks shortward of 10 μm, assuming a reasonable state-of-the-art detection system. Ten and 20 μm are on the Rayleigh-Jeans tail of the stellar blackbodies, so stellar fluxes are lower than at the shorter wavelengths; in addition, the thermal background degrades detection limits. Thus, the critical question is how good a standard network can be obtained at these wavelengths. This question has been addressed by drawing up a preliminary network and examining its characteristics.

E.2 Preliminary Standard Star Network

The preliminary network contains 48 prime stars, with an additional 18 secondary stars of somewhat lower quality. The prime list was selected according to the following criteria:

a. IRAS band 2 (25 μm) magnitude ≤ 0.

b. Spectral type between A0 and K7.

c. No variability.

d. No IR excess.

The secondary network includes stars with

a. IRAS band 2 (25 μm) magnitude ≤ −1.

b. Spectral type between *A0* and *M5*.

c. Variability at V (0.56 μm) ≤ 0.4 magnitudes.

d. No strong IR excess.

The secondary list contains nearly all *M* stars with small-amplitude, "semiregular" variability. It is expected that the range of variation will be less in the IR, because of the reduced temperature dependence of flux on the Rayleigh-Jeans tail. As a rule of thumb, IR variability should be about one third the visible ranges. In addition, the M stars can be expected to have larger mass loss and hence may have IR features due to dust in circumstellar shells, and their photospheric absorption features will be very strong, making correction to arbitrary bands more difficult than for members of the prime list.

These lists are attached as Tables E-1A and E-1B. The distribution of the proposed network in the sky is illustrated in Figure E-1. Particularly with the addition of the secondary list, this network is well distributed in the sky, and it would provide a greatly improved basis for all photometry at these wavelengths.

E.3 The Q Problem

For some experiments, it is desired at 20 μm to have calibrators that are at magnitude −3 or brighter. The proposed network has only four stars this bright, two from the prime list and two from the secondary one. There are at least three forms of tertiary networks that could be used to address this problem.

Asteroids have the advantage of having smooth spectra that are relatively easy to model to adjust measurements to other bands. They are also point-like. Their positions are not fixed, but they can be obtained accurately with sufficient effort; however, they cannot provide all-sky coverage because they are grouped along the ecliptic, and at any given time even a significant zone of ecliptic can be free of bright asteroids. Moreover, they have variability with earth-asteroid-sun phase angle, and many vary with rotation (hence on short time scales) because of emissivity variations over their surfaces.

Compact HII regions and planetary nebulae are nonvariable and fixed on the sky. However, their spectra are complex and will vary strongly from one to the other. In addition, they are extended objects. HII regions will tend to be distributed only along the galactic plane.

Bright IR stars are fixed on the sky and point-like. They are variable, but have long time scales (~200 days or more). Their spectra will bear some family resemblances to each other but will have much more variety than is desirable to trace measurements to other spectral bands.

TABLE E-1A

Primary Standard List

	HR	name	α2000			δ2000			spectrum	m_v	m_{12}	m_{25}
1.	99	α Phe	00^h	26^m	17^s 0	−42°	18'	22"	K0III	2.4	−0.7	−0.7
2.	165	δ And	00	39	19.6	+30	51	40	K3III	3.3	−0.1	−0.1
3.	188	β Cet	00	43	35.3	−17	59	12	K0III	2.0	−0.8	−0.8
4.	603	γ And	02	03	53.9	+42	19	47	K3IIb	2.3	−1.3	−1.4
5.	617	α Ari	02	07	10.3	+23	27	45	K2IIIab	2.0	−1.1	−1.2
6.	1017	α Per	03	24	19.3	+49	51	41	F5Ib	1.8	0.0	0.0
7.	1393	43 Eri	04	24	02.1	−34	01	01	K4III	4.0	0.0	−0.1
8.	1457	α Tau	04	35	55.2	+16	30	33	K5III	0.8	−3.5	−3.4
9.	1577	ι Aur	04	56	59.6	+33	09	58	K3II	2.7	−1.2	−1.2
10.	1654	ε Lep	05	05	27.6	−22	22	16	K5III	3.2	−0.7	−0.9
11.	1708	α Aur	05	16	41.3	+45	59	53	G5III	0.1	−2.3	−2.3
12.	2326	α Car	06	23	57.2	−52	41	44	F0II	−0.7	−1.8	−1.8
13.	2491	α CMa	06	45	08.9	−16	42	58	A1V	−1.5	−1.7	−1.7
14.	2553	τ Pup	06	49	56.1	−50	36	53	K1III	2.9	−0.2	−0.2
15.	2773	π Pup	07	17	08.5	−37	05	51	K3Ib	2.7	−1.6	−1.7
16.	2878	σ Pup	07	29	13.8	−43	18	05	K5III	3.2	−0.9	−1.0
17.	2943	α CMi	07	39	18.1	+05	13	30	F5IV	0.4	−1.1	−1.1
18.	2990	β Gem	07	45	18.9	+28	01	34	K0IIIb	1.1	−1.6	−1.6
19.	3275	31 Lyn	08	22	50.1	+43	11	17	K4III	4.2	0.0	0.0
20.	3307	ε Car	08	22	30.8	−59	30	34	K3III	1.9	−2.3	−2.4
21.	3705	α Lyn	09	21	03.2	+34	23	33	K7III	3.1	−1.2	−1.2
22.	3748	α Hya	09	27	35.2	−08	39	31	K3II	2.0	−1.8	−1.7
23.	4094	μ Hya	10	26	05.4	−16	50	11	K4III	3.8	−0.1	−0.1
24.	4232	ν Hya	10	49	37.4	−16	11	37	K2III	3.1	−0.2	−0.2
25.	4301	α UMa	11	03	43.6	+61	45	03	K0III	1.8	−1.2	−1.2

TABLE E-1A (Continued)

Primary Standard List

	HR	name	α2000			δ2000			spectrum	m_v	m_{12}	m_{25}
26.	4335	ψ UMa	11	09	39.7	+44	29	54	K1III	3.0	–0.1	–0.1
27.	4630	ε Crv	12	10	07.4	–22	37	11	K2III	3.0	–0.4	–0.4
28.	5288	ϑ Cen	14	06	40.8	–36	22	12	K0III	2.1	–0.7	–0.7
29.	5340	α Boo	14	15	39.6	+19	10	57	K1III	0.0	–3.6	–3.5
30.	*5459	α Cen	14	39	36.2	–60	50	07	G2V/K1V	0.0	–2.2	–2.2
31.	5563	β UMa	14	50	42.2	+74	09	20	K4III	2.1	–1.9	–1.9
32.	5705	φ Lup	15	21	48.3	–36	15	41	K5III	3.6	–0.6	–0.6
33.	5854	α Ser	15	44	16.0	+06	25	32	K2III	2.6	–0.4	–0.4
34.	6217	αTrA	16	48	39.9	–69	01	40	K2IIb	1.9	–1.7	–1.7
35.	6229	η Ara	16	49	47.0	–59	02	29	K5III	3.8	–0.6	–0.6
36.	6241	ε Sco	16	50	09.7	–34	17	36	K2III	2.3	–0.6	–0.7
37.	6285	ρ Ara	16	58	37.1	–55	59	24	K3III	3.1	–1.1	–1.1
38.	6418	π Her	17	15	02.7	+35	48	33	K3II	3.2	–0.5	–0.6
39.	6461	β Ara	17	25	17.9	–55	31	47	K3Ib	2.8	–0.8	–0.9
40.	6603	β Oph	17	43	28.3	+04	34	02	K2III	2.8	–0.3	–0.3
41.	6859	δ Sgr	18	20	59.6	–29	49	41	K3III	2.7	–0.8	–0.9
42.	6913	λ Sgr	18	27	58.1	–25	25	18	K1III	2.8	–0.1	–0.1
43.	7417	β Cyg	19	30	43.2	+27	57	35	K3II	3.1	–0.3	–0.4
44.	7525	γ Aql	19	46	15.5	+10	36	48	K3II	2.7	–1.1	–1.2
45.	7557	α Aql	19	50	46.9	+08	52	06	A7V	0.8	–0.1	–0.2
46.	7949	ε Cyg	20	46	12.6	+33	58	13	K0III	2.5	–0.4	–0.4
47.	8079	ξ Cyg	21	04	55.8	+43	55	40	K4Ib	3.7	–0.2	–0.2
48.	8502	α Tuc	22	18	30.1	–60	15	35	K3III	2.9	–0.8	–0.8

* HR 5459: Binary at ~0.1 mr; both stars contribute to IR flux.

TABLE E-1B

SECONDARY STANDARD LIST

HR		name	α2000			δ2000			spectrum	m_v	m_{12}	m_{25}
1.	337	β And	01^h	09^m	43^s9	+35°	37'	14"	M0III	2.1	−2.5	−2.5
2.	*555	ψ Phe	01	53	38.7	−46	18	10	M4III	4.4	−1.2	−1.3
3.	*911	α Cet	03	02	16.7	+04	05	23	M1.5III	2.5	−2.3	−2.3
4.	1208	γ Hyi	03	47	14.5	−74	14	21	M2III	3.2	−1.5	−1.5
5.	*2286	μ Gem	06	22	57.6	+22	30	49	M3III	2.9	−2.6	−2.6
6.	4069	μ UMa	10	22	19.7	+41	29	58	M0III	3.0	−1.1	−1.1
7.	4763	γ Cru	12	31	09.9	−57	06	47	M3.5III	1.6	−3.7	−3.8
8.	4910	δ Vir	12	55	36.1	+03	23	51	M3III	3.4	−1.9	−1.9
9.	*5603	σ Lib	15	04	04.1	−25	16	55	M3III	3.3	−2.1	−2.0
10.	6056	δ Oph	16	14	20.6	−03	41	40	M0III	2.7	−1.8	−1.8
11.	*6020	δ Aps	16	20	20.7	−78	41	45	M5III	4.7	−1.3	−1.4
12.	*6705	γ Dra	17	56	36.3	+51	29	20	K5III	2.2	−1.8	−1.9
13.	*6832	η Sgr	18	17	37.5	−35	45	42	M3.5III	3.1	−2.2	−2.2
14.	*7536	δ Sge	19	47	23.2	+18	32	03	M2II	3.8	−1.4	−1.4
15.	*7650	62 Sgr	20	02	39.4	−27	42	36	M4III	4.6	−1.3	−1.5
16.	*8636	β Gru	22	42	40.0	−46	53	05	M5III	2.1	−3.8	−3.9
17.	*8698	λ Aqr	22	52	36.8	−07	34	47	M2III	3.7	−1.3	−1.3
18.	*8775	β Peg	23	03	46.4	+28	04	58	M2.5II	2.4	−2.5	−2.5

* HR 555: variable star; ΔV = 0.20
* HR 911: variable star; ΔV = 0.06
* HR 2286: variable star; ΔV = 0.26
* HR 5603: variable star; ΔV = 0.16
* HR 6020: variable star; ΔV = 0.21
* HR 6705: variable star; ΔV = 0.08
* HR 6832: variable star; ΔV = 0.04
* HR 7536: variable star; ΔV = 0.09
* HR 7650: variable star; ΔV = 0.16
* HR 8636: variable star; ΔV = 0.30
* HR 8698: variable star; ΔV = 0.10
* HR 8775: variable star; ΔV = 0.43

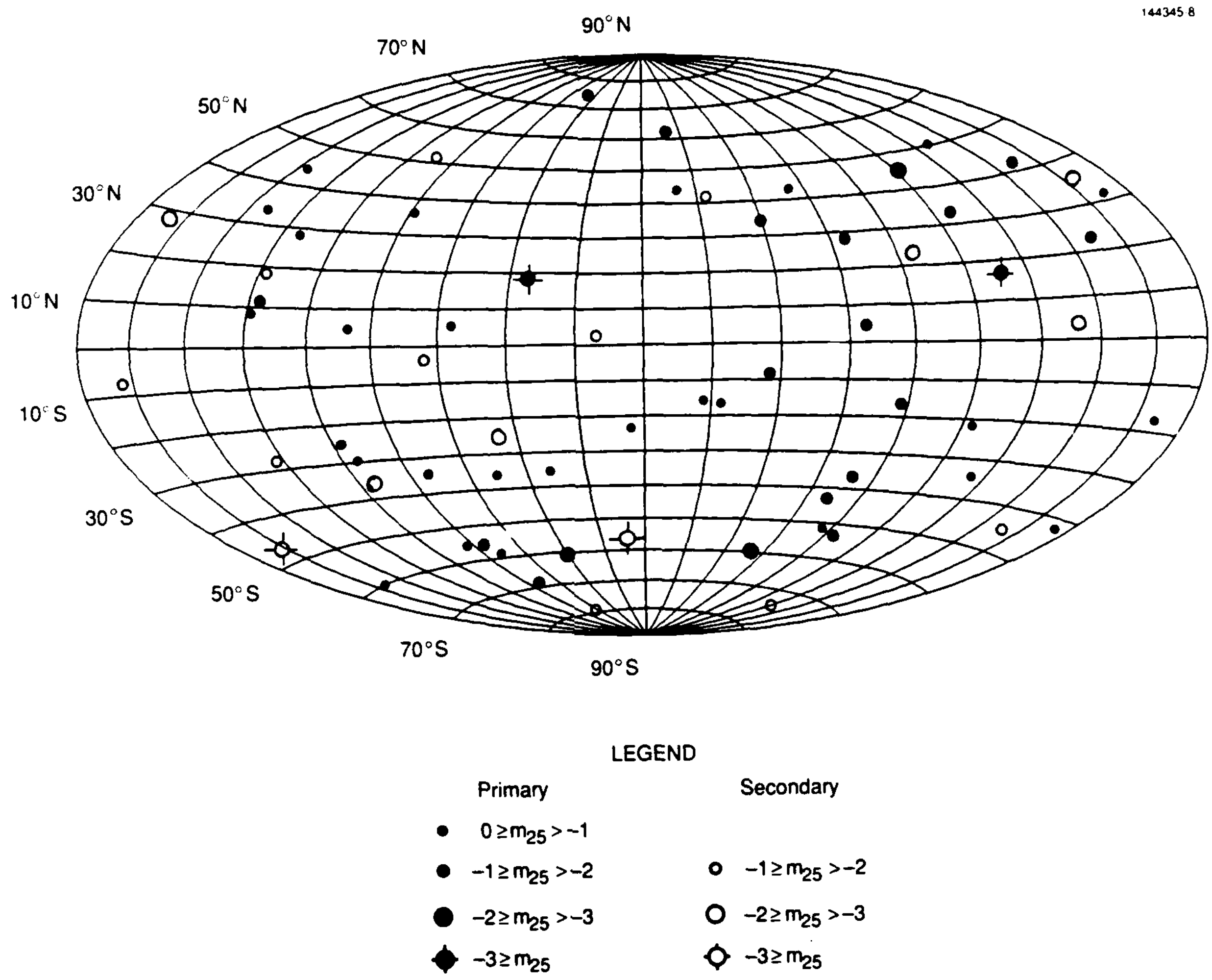

Figure E-1. Distribution of proposed standard stars.

Of these choices, the most satisfactory appears to be the bright IR stars. A check of 25 percent of the sky shows that there should be 80 to 100 of these objects brighter than –3 at 20 μm, well distributed over the whole sky. Three steps need to be taken to use these objects as calibrators:

a. The standard star network needs to be established to permit accurate differential measurements of the bright IR stars.

b. The IR stars need to be observed thoroughly over a variation cycle, so the changes in spectral characteristics can be derived. These changes should repeat fairly closely over future cycles.

c. Close to the time the star is used as a calibrator (preferably within one week), it should be compared with a member of the standard network to establish its current brightness level.

E.4 SUMMARY

For wavelengths out through 10 μm, a conventional standard star network can be established that has enough bright members distributed over the sky to meet our requirements. At 20 μm, experiments requiring very bright reference stars will need to use variable stars. Because the timescale of variability is long, an accurate reference can still be achieved if the star is referred to a member of the standard network within one week of the measurement, and if the spectral properties of the reference star during its variability cycle have been determined either in advance or as part of the measurement series.

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13. ABSTRACT *(Maximum 200 words)*

Data requirements are derived for stellar infrared spectra to be used for calibration reference in a generalized, defense-related program. A program to create such a data set is outlined. The data set would be usable by a variety of users and would both simplify the calibration process and facilitate program-to-program comparisons.

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