THELI: CONVENIENT REDUCTION OF OPTICAL, NEAR-INFRARED, AND MID-INFRARED IMAGING DATA

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ABSTRACT

The last 15 years have seen a surge of new multi-chip optical and near-IR imagers. While some of them are accompanied by specific reduction pipelines, user-friendly and generic reduction tools are uncommon. In this paper I introduce THELI, an easy-to-use graphical interface driving an end-to-end pipeline for the reduction of any optical, near-IR, and mid-IR imaging data. The advantages of THELI when compared to other approaches are highlighted. Combining a multitude of processing algorithms and third party software, THELI provides researchers with a single, homogeneous tool. A short learning curve ensures quick success for new and more experienced observers alike. All tasks are largely automated, while at the same time a high level of flexibility and alternative reduction schemes ensure that widely different scientific requirements can be met. Over 90 optical and infrared instruments at observatories world-wide are pre-configured, while more can be added by the user. The Appendices contain three walk-through examples using public data (optical, near-IR, and mid-IR). Additional extensive documentation for training and troubleshooting is available online.

Key word: techniques: image processing

Online-only material: color figure

1. INTRODUCTION

The systematic introduction of CCDs revolutionized the field of observational astronomy at the beginning of the 1980s (see, e.g., Crane et al. 1981; Goad & Ball 1981; Gunn & Westphal 1981; McLean et al. 1981; Mortara & Fowler 1981). It was paralleled by the development of large software packages to process these new kinds of data, such as IRAF (Butcher & Stevens 1981; Valdes 1984), ESO-MIDAS (Banse et al. 1983), and STARLINK (Pavelin & Walter 1980). These programs have become deeply tied to observational astronomy. They form an integral part of the observing and data acquisition software at many observatories, and numerous reduction packages have been built based on them.

At the end of the 1990s the limited field of view of a single CCD was overcome by mosaic cameras, such as the Wide-Field Imager on the Anglo-Australian Observatory (AAO), the Wide-Field Imager on the 2.2m MPG/ESO telescope (Baade et al. 1999), CFH12K on the Canada–France–Hawaii Telescope (CFHT; Cuillandre et al. 2000), and the SuprimeCam of Subaru (Miyazaki et al. 2002) in the optical, and CIRS1 on the William Herschel Telescope (WHT; Beckett et al. 1997) in the near-IR. In the following, these and other instrument.telescope combinations will be abbreviated in the format WFI@AAO. Since the 1990s, deep and wide surveys have become possible, drastically increasing the volume of data produced per night. While the new instruments have been used frequently from the start, the volumes and much increased complexity of the data have proved a challenge for the first few years as corresponding software support lagged behind. In particular, astrometric and photometric solutions have become non-trivial and tiresome now that dithered images from detector mosaics with distortion patterns have to be combined. This has triggered the development of many astrometric pipelines outside the IRAF or MIDAS context, such as WIFIX\textsuperscript{4}, the LDAC pipeline\textsuperscript{5}, and Scamp (Bertin 2006), to name just a few.

New survey telescopes such as the VLT Survey Telescope (VST), VISTA, and the future LSST are pushing the boundaries further, combining extreme optics with detector mosaics of up to a hundred CCDs or more (e.g., DECam@CTIO, Flaugher et al. 2012; GPC1@Pan-Starrs, Onaka et al. 2008; HyperSuprimeCam@Subaru, Miyazaki et al. 2012; ODI@WIYN, Jacoby et al. 2002; OmegaCam@VST, Kuijken et al. 2002; VIRCAM@VISTA, Hummel et al. 2010). While some of these cameras are used mostly for public surveys, others are facility instruments available to private investigators (PIs). The associated data reduction pipelines are not necessarily publicly available (e.g., VISTA) or portable to the PI’s computer, as they may be tied to large commercial data base applications.

Data processing is made even more challenging by the multitude of optical and near-IR data we combine for our research. It is common that exposures from several telescopes and cameras are pooled for one project, providing sufficient sample sizes and/or a multi-wavelength perspective. Frequently, researchers have to switch to new and unfamiliar software to ensure consistent data quality, a time-consuming and demanding task. Custom-made reduction scripts and methods are no longer interchangeable between instruments.

In 2000, Thomas Erben and I faced these problems for our 20 deg\textsuperscript{2} weak lensing survey (Schirmer et al. 2003) and decided to develop an instrument-independent pipeline that could process data from any future, optical multi-chip camera. We exploited existing, stand-alone software solutions (mostly Astromatic\textsuperscript{6} and LDAC), and merged them with custom-made modules to ensure a fast and smooth data flow. This

\textsuperscript{4} M. Radovich, http://www.aa.astro.it/~radovich/wifix.htm
\textsuperscript{5} E. Deul, ftp://ftp.strw.leidenuniv.nl/pub/ldac/software/
\textsuperscript{6} http://www.astromatic.net
THELI pipeline core is operated by a number of command-line scripts, and has been developed on data from WFI@2.2m MPG/ESO and MegaCam@CFHT. Its main purpose is the reduction of large survey data sets, such as the CFHT Lensing Survey (CFHTLenS; Erben et al. 2013), utilizing Linux cluster architectures. The pipeline, presented in Erben et al. (2005, hereafter E05), has been extensively tested (e.g., Hildebrandt et al. 2006; Erben et al. 2013).

The command-line approach for mass production competed with the goal of creating an instrument-independent pipeline to be used by a PI for his or her individual projects. Hard-coded parameters and manual editing of configuration files were just some of the obstacles faced. Another problem is that the command-line scripts have been optimized for the reduction of blank fields, and do not work (well) for crowded fields or significantly extended sources. To overcome these issues I started developing a THELI graphical user interface (GUI). It includes many new tasks such as alternative astrometric routines and more adaptive sky subtraction methods. In addition to full near- and mid-IR support it also handles all administrative tasks for the user. Thus, a highly flexible and convenient tool able to process essentially all kinds of imaging data now exists. It facilitates a broad range of scientific studies, ranging, e.g., from the optical distortion modeling of the LORRI camera on board the New Horizons mission (McMichael & Bentley 2012) or the Deep Impact campaign (Meech et al. 2005), via the expansion history of planetary nebulae (Santander-García et al. 2008) to studies of galaxy clusters (Lieder et al. 2012). THELI’s command-line version has been used for several large survey projects, such as a systematic lensing study of 51 of the most X-ray luminous galaxy clusters known (von der Linden et al. 2012), and the CFHTLenS (comprising 154 deg$^2$; Heymans et al. 2012).

This paper contains a description of the THELI GUI’s (version 2.8.1) most important features. An additional comprehensive user manual and technical reference is available online. For the remainder of this paper, THELI refers to the GUI. Section 2 contains a short overview of the working principle, and discusses software prerequisites for installation. Section 3 covers the preparation of the data, nonlinearity, and cross-talk corrections. In Section 4 the various options available for background modeling are explained. This is followed by a short summary about weighting and bad pixel mapping in Section 5, with astrometric and photometric calibration in Section 6. Sky modeling is addressed in Section 7, and the various options available for final image coaddition are given in Section 8. A short summary and outlook is presented in Section 9. Appendices A–C contain three step-by-step reduction examples, based on public optical, near-IR, and mid-IR images. A list of currently supported instruments is included at the end.

2. STRUCTURE AND OPERATION OF THELI

Most data processing algorithms in THELI are not new inventions but have been used before. The big advantage of THELI is that a multitude of procedures has been combined into and made accessible via a single, homogeneous tool. Figure 1 shows the Initialize section of THELI’s user interface, where global information is provided, such as the current project title, how many CPUs to use, where the data can be found, and the instrument with which they were taken. Thereafter, the user proceeds through six sections to arrive at a coadded image. The main aspects of these sections are discussed in this paper, with concrete examples given in the appendices.

7 http://www.astro.uni-bonn.de/~theli/gui
2.1. Software Prerequisites and Implementation

Most software modules developed for THELI, as well as third party programs such as the Astromatic tools, are written in C/C++. They are compiled with standard tools such as gcc and make, and do not require exotic libraries. A few other modules are based on the python language. The user interface itself is based on the C/C++ Qt library, which is also the heart of many Desktop environments such as KDE. All these prerequisites are fundamental parts of modern Linux systems and available in pre-compiled form in their respective repositories. As such, THELI can be compiled on essentially all Linux platforms and has sufficient backward compatibility.

The only current shortcoming is that THELI does not compile under MacOS. This can be overcome by installing a Linux guest operating system in a virtual machine, at the cost of performance. THELI is currently based on Qt3, which is being phased out in future Linux releases, but can always be compiled from source. In the near future, THELI will be ported to the recently released Qt5 library, and offer full support for MacOS.

3. CORRECTING HEADERS AND DETECTOR FEATURES

3.1. Homogenizing FITS Headers

The first step in THELI is to bring all FITS headers from different instruments to a common format, taking into account possible header changes made over time. This is essential for an instrument-independent pipeline to work, as not all FITS headers adhere to the FITS standard. For example, conflicting keywords such as CD1.j and FC1.j may appear simultaneously, or the instrument’s orientation on sky is unknown. Likewise, the World Coordinate System (WCS) information may be inaccurate or have to be reconstructed from nonstandard keywords. Invalid key values such as negative airmass values have to be corrected as well. In general, more intricate problems such as incorrect filter names cannot be detected automatically. Thus, it is the user’s responsibility to validate the integrity of the raw data.

Consequently, THELI modifies the original FITS header, retaining and translating only keywords essential for data reduction. Apart from mandatory keywords, the new header comprises a complete set of WCS keywords; date and time; and a few others such as airmass, filter, and exposure time. Additional keywords to be retained can be defined by the user. Multi-extension FITS files are split into individual chips for parallelization purposes at this point of the processing.

3.2. Cross-talk

Different forms of cross-talk (Figure 2) may appear in detectors with multiple readout channels. Intra-chip normal cross-talk causes ghost images of a bright source in the other channels. Row cross-talk enhances the values of the rows (or columns) containing a bright source, and the same feature is projected into the other readouts (for an example see Freyhammer et al. 2001). These effects are fixed by subtracting a rescaled image (or scaled average row values) of the offending channel from the other channels. Both forms of cross-talk may appear simultaneously.

\[ x_{\text{lin}} = \sum_{i=0}^{3} a_i x_0^i, \]

where \( x_0 \) are the pixel values in the uncorrected exposure. The coefficients \( a_i \) are stored in a separate configuration file. Currently, only a few instruments (such as WFC@INT) are pre-configured for non-linearity correction. Coefficients for other instruments can be added by the user.

After these preparatory steps, the user creates a master bias and a master flat, and applies them to the data. This is a straightforward process and described in the example reductions in the appendices.

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8 The command-line version, however, using the pipeline core only, does compile under MacOS.
9 http://download.qt-project.org/archive/qt3/
10 http://fits.gsfc.nasa.gov/fits_standard.html
4. BACKGROUND MODELING AND ZERO-POINT VARIATIONS

THELI distinguishes between background modeling and sky subtraction. A background model is a median combination of several successive and dithered exposures, correcting for residual variations after flat-fielding. Depending on the cause of the variations, the images must be divided (“superflatted”) by the model, or the model is subtracted. The latter is typically the case for near-IR observations and removes most of the sky signal. Sections 4.1 and 4.1.1 show different ways of creating a background model. Sky subtraction, by contrast, is based on single images and eliminates any remaining individual gradients or pedestals (see Section 7).

Background variations may change over time. Possible causes include both additive and multiplicative effects, such as
1. improper illumination of the domeflat screen,
2. scattered light in twilight flats,
3. moonlight,
4. airglow (particularly in the near-IR),
5. sky concentration (reflection between CCD and corrector lenses or filters), and
6. fringing.

Spatial zero-point variations occur when additive and multiplicative components are mixed in a flat field. They result from either external scattering (e.g., unfavorable dome orientation during twilight) or internal reflections in the instrument. The amplitudes of these variations can reach up to 10%. A direct comparison of stellar magnitudes in dithered data is required. A comparison with known reference sources in the field can also be performed to solve this problem (Manfroid et al. 2001; Koch et al. 2004). The latter approach is available in THELI (Section 6.1), yielding single zero-point adjustments for individual chips but not yet a full two-dimensional (2D) correction. For instruments that are mostly used for survey work, the corresponding 2D corrections are usually included in a dedicated pipeline (e.g., VIRCAM@VISTA), or directly applied to pre-processed archival data (e.g., MegaCam@CFHT, using the ELIXIR pipeline; Magnier & Cuillandre 2004).

4.1. Static and Dynamic Background Models

A static background model is a single median image created from a series of exposures. It can be applied to all images from which it was created, and is rescaled to correct for slow, global variations. A good example of this is a background model created from a 10–30 minute long sequence of short near-IR exposures. Atmospheric airglow changes little during this time, and thus a single static model is sufficient to subtract the sky. Another example of this type of model would be a classic optical superflat computed from data taken on a clear night.

A dynamic background model is needed if sky conditions are unstable during a series of exposures. This is generally the case for any near-IR sequence extending over more than 10–30 minutes, as the airglow changes the sky brightness on time scales of minutes with spatial fluctuations on scales of arcminutes. Optical i- or z-band data may also require dynamic correction. THELI creates the background model for the kth exposure from the m closest exposures in time. The latter may or may not bracket the kth exposure symmetrically.

Common to both approaches is that all objects are masked prior to the creation of the model, and the highest pixel in the stack is rejected. These settings can be adjusted arbitrarily.

THELI also supports two-pass background subtraction, which may be required in the near-IR for extended objects or very deep observations (see Appendix B for an example processing flow). The quality of THELI’s background models is illustrated in Figure 3, revealing two extended tidal debris features of low surface brightness around a random field galaxy (see also Martínez-Delgado et al. 2010).

An exposure sequence containing one or more longer interruptions is not adequately represented by a single background model. If the interruptions exceed a user-specified amount of time, separate background models are automatically calculated for each group of images and applied accordingly.

4.1.1. Separate Sky Observations

The variable near-IR background requires larger dither patterns in the presence of extended objects to be able to estimate the sky at the object’s position. A nearby blank field has to be observed in a periodic manner if the target comprises about half the detector’s field-of-view or more. This may also become necessary for optical observations if an accurate correction is required. Exposures of a blank area should be kept in a separate SKY directory where they are found and processed by THELI.

4.2. Removing Linear Gradients

Some HAWII arrays show residual linear gradients after background modeling, leading to discontinuities between readout quadrants. This detector reset anomaly may depend on exposure time, sky brightness, the time passed between exposures, detector temperature, etc. It is corrected by subtracting an average row or column calculated from the
affected area. This collapse correction also supports HAWII-2 arrays with four quadrants and alternating 90° orientation (see Figure 4).

4.3. Mid-IR Observations

Ground-based mid-IR observations require special observing techniques as the background signal is very high (−5 to −7 mag arcsec−2). To remove the rapidly varying sky, the secondary mirror is tilted (chopped) every few seconds, projecting an empty sky area in the immediate vicinity of the target onto the detector. The second image is then subtracted from the first one. However, the thermal signal from the telescope does not cancel out entirely since the detector sees the telescope from slightly different angles at the two chopper positions. The telescope is therefore offset slightly (a process known as nodding), and another series of chopped images is taken at the new position. A new difference image is calculated from the chopped images at the second nod position. Finally, by subtracting the second difference image from the first difference image, the residual thermal signal is removed. If the order of science and sky observations are reversed at the second nod position, the difference images have to be added (see Figure 5). As the telescope’s temperature changes only slowly, the nodding is usually done once or twice per minute.

Data formats and the amount of information stored in the raw data vary greatly between mid-IR instruments. T-ReCS@GEMINI, for example, averages the 2D individual exposures obtained at a given chop/nod position and sorts them into a four-dimensional hyper-cube, where the two extra dimensions specify (1) the telescope’s nod position and (2) whether the chopper observed the sky or the target. Sky exposures with T-ReCS are unguided and generally discarded after processing due to inferior quality. A typical chop-nod cycle lasts several minutes and is stored as one hyper-cube. An arbitrary number of such hyper-cubes may be contained in separate FITS extensions. THELI performs the chop-nod sky subtraction during initial data preparation. It writes out either a single 2D FITS image, representing the fully stacked hyper-cube, or one image for every chop-nod cycle.

The other currently supported mid-IR camera is VISIR@VLT. Currently a generic chop-nod module is available for thermal background removal. This will be replaced by individually optimized routines (such as for T-ReCS) once more mid-IR cameras are implemented in THELI. A VISIR image processed with THELI is shown in Figure 6.

5. Weighting and Defect Detection

The general weighting process has been described in detail in E05. To summarize, a weight map is created based on the normalized flat. This global weight is then modified individually to mask cosmics, hot pixels, or satellites present in the images.

Many CCDs suffer from bad columns, some of which cannot be corrected using dark exposures. THELI is able to identify such defects (even weak ones) in a well exposed flat field. The variations in a flat field due to uneven illumination are often larger than those caused by bad columns. These effects must therefore first be corrected for, which is done by dividing the flat field by itself after convolution with a 30 pixel wide Gaussian. The mean value of an individual column is then compared to the overall mean of the image. The column will be masked if it deviates by more than a user-defined threshold (default: 2%).

6. Photometry and Astrometry

6.1. Direct Photometric Calibration

Direct photometric calibration means that the zero-point of an individual exposure is obtained from stars of known magnitude within the same field. Currently, SDSS-DR9 (Ahn et al. 2012) and 2MASS (Skrutskie et al. 2006) catalogs are available in THELI for this purpose. A (configurable) maximum uncertainty of 0.05 mag is allowed for the reference magnitudes. Future deeper/wider surveys will be implemented as they become publicly available.

This method has three advantages compared to the classic indirect calibration. First, the data can be taken in arbitrary photometric conditions. Second, multi-chip cameras can be corrected for residual zero-point differences between chips (see, e.g., Schirmer et al. 2011). Third, no observing time has to be reserved for standard stars at different airmass. On the downside, possible color terms remain undetermined.

6.2. Indirect Photometric Calibration

In E05 we describe photometric calibration using standard stars and a three parameter fit (zero-point, color term, extinction). Only the bright UBVRI standards by Landolt (1992) and Stetson (2000) were implemented at the time. Today THELI provides the SDSS stripe 82 photometric calibration catalog (Ivezić et al. 2007) in addition, covering 20:30:00 < R.A. < 04:00:00, and −01:16:00 < decl. < 01:16:00. Originally this catalog contains 1.01 million point sources, but only objects with photometric errors <0.05 mag in all bands are kept. Very faint sources in the gri filters, which could lead to a systematic bias of 0.02 mag in the zero-point, have also been removed. 340,000 sources remain, all of which have ugriz magnitudes in the SDSS 2.5 m system as well as u′g′r′i′z′ in the USNO 1.0 m system (Smith et al. 2007). The catalog has to be downloaded separately from the THELI Web site.

For near-IR data, JHK, magnitudes from Leggett et al. (2006; UKIRT MKO), Hunt et al. (1998), and Persson et al. (1998) are available, as well as the 2MASS calibration fields by Nikolaev et al. (2000). A combined YJHK_sLm catalog from UKIRT/JAC has also been added, together with L/M′ data from Leggett et al. (2003).

6.3. Astrometry

Astronomical instruments cover very small to very large fields of view, hence absolute astrometric calibrations rely on suitably chosen reference catalogs. Extreme cases are, e.g., near-IR data of a small field with low source density or wide-field images of
the crowded galactic plane. Successful matching of source and reference catalogs requires sufficient mutual overlap. A variety of adjustments are available if matching with default values fails:

1. Depth of the reference catalog (to avoid computational limits for crowded fields),
2. Depth of the SExtractor (Bertin & Arnouts 1996) source catalog,
3. Deblending of composite sources (e.g., richly structured galaxies),
4. Filters to reject spurious sources,
5. Various reference catalogs (e.g., for greater depth or better wavelength match), and
6. Different matching algorithms.

Currently implemented catalogs are SDSS-DR9, PPMXL, USNO-B1, 2MASS, UCAC-4, GSC-2.3, and Tycho (Ahn et al. 2012; Roeser et al. 2010; Monet et al. 2003; Cutri et al. 2003; Zacharias et al. 2012; Lasker et al. 2008; Perryman & ESA 1997, respectively). Tycho can be used for images taken with wide angle photo lenses covering hundreds of square degrees. For all-sky camera data, a locally stored, filtered version of GSC-2.3 with an upper magnitude limit of 10 is available.

Sometimes these catalogs are insufficient, e.g., if the target is a bright and richly structured nearby galaxy. The reference catalog might be empty because the photographic plate was saturated or the source deblending was insufficient. In this case, secondary reference catalogs can be created with THELI from images with valid WCS headers taken with another telescope (see, e.g., Section 6.3.5).

The astrometric solution is stored in separate FITS headers, which are read by SWarp (Bertin 2010) during image coaddition. The individual images remain uncorrected, unless the Update header function is used, inserting the first order solutions (CRPIX1/2, CRVAL1/2, and CDij) into the headers. This is optional and can be undone at any time. If fully distortion-corrected individual images are needed, the resampled data (Section 8.1.1) can be utilized.

6.3.1. Scamp

The most commonly used astrometric tool in THELI is Scamp (Bertin 2006), developed in particular for multi-chip cameras. Previously stored information about the detectors’ relative orientation (the focal plane, hereafter FP) can be used. To this end the FP has been measured for all pre-configured multi-chip cameras in THELI (Tables 4 and 5, Appendix D) based on dense stellar fields. FP models may need updates from time to time, e.g., if an instrument has undergone mechanical or optical maintenance. In cases where the detectors are not located in the same physical plane (e.g., VIMOS@VLT, SPARTAN@SOAR), differential flexure between the optical arms may require the FP model to be updated for each data set. This functionality is readily available in THELI.

The internal accuracy of the resulting astrometric solution with Scamp is on the order of 0.06–0.12 pixels for optical wide-field imagers (see, e.g., Erben et al. 2013). For low
density fields observed in the near-IR it may be reduced to 0.1–0.3 pixels. Once the astrometric solution is obtained, \texttt{Scamp} also determines relative photometric zero-points for the exposures.

\texttt{Scamp} matches the object catalogs to the astrometric reference catalog as follows. In the first step, the pixel scale and relative position angle are determined for both catalogs by “cross-correlating the 2D histograms of source pair coordinates in the log(separation) vs. position-angle space” (Bertin 2006, “cross-correlating the 2D histograms of source pair coordinates and relative position angle are determined for both catalogs by reference catalog as follows. In the first step, the pixel scale and relative photometric zero-points. While automatically afterward (with matching deactivated) to calculate distortion maps and relative photometric zero-points. This approach works well as long as the positional uncertainty is not too large, i.e., the offset between nominal and true coordinates is not larger than about half the field of view. However, this condition is not always met, which can make the astrometric solution difficult (in particular if the position angle and a possible flip are still undetermined, e.g., for commissioning data).

6.3.2. \texttt{astrometry.net}

A complementary solution to \texttt{Scamp} is a local implementation of the \texttt{astrometry.net} algorithm (Lang et al. 2010). Matching is based on quadrilaterals in the reference and the object catalogs. \texttt{astrometry.net} can create its own source catalogs, but in \texttt{THELI} it will use the same \texttt{SExtractor} catalogs as created for \texttt{Scamp}. In this way the user has more control over source densities and spurious detections. \texttt{THELI} does not use the \texttt{astrometry.net} all-sky online index, but builds the (much smaller) reference index from the reference catalog. By running the \texttt{astrometry.net} client locally, an exposure with a few hundred to a thousand sources is typically solved within a fraction of a second.

The different matching techniques used by \texttt{Scamp} and \texttt{astrometry.net} complement each other for problematic fields. The disadvantages of the current implementation of \texttt{astrometry.net} (v0.43) include its inability to calculate relative photometric zero-points, while also offering little control over how e.g., distortion or chip alignment are handled, in particular, for multi-chip cameras. \texttt{astrometry.net} calculates the distortion polynomial coefficients in the SIP convention (Shupe et al. 2012), which is not understood by \texttt{SWarp} which uses the older PV convention. Hence \texttt{astrometry.net} is currently used for catalog matching only, while \texttt{Scamp} is run automatically afterward (with matching deactivated) to calculate the distortion maps and relative photometric zero-points.

6.3.3. Shift and Cross-correlation for Mid-IR Data

Both \texttt{Scamp} and \texttt{astrometry.net} deliver full WCS solutions. However, they need sufficiently high object density to constrain all parameters. This is never the case for mid-IR data, where fields of view are (1) on the order of a few tens of arcseconds and (2) contain only one or a few sources (possibly all of which are non-stellar). In addition, suitable all-sky mid-IR catalogs with sufficient spatial resolution are not available. Thus for mid-IR data, \texttt{THELI} simply measures the linear shift between exposures in image coordinates and constructs a dummy WCS solution that is understood by \texttt{SWarp} for stacking.

Two methods are available. In the first, the Shift approach is based on \texttt{SExtractor} catalogs and recommended for data in which one (or a few) point source(s) can be repeatedly detected in all images. Relative photometric zero-points are determined as well. In the second method, the offsets are determined using 2D cross-correlation of noise clipped images. This approach is recommended for data with predominantly extended flux.

6.3.4. Adopting the Original WCS Header

If an astrometric solution cannot be found with either of the above methods, then the user can simply adopt the zero-order WCS solution already present in the raw FITS headers. Only \texttt{CRPIX1}/2, \texttt{CRVAL1}/2, and the \texttt{CD}-matrix will be copied in this case, while distortion terms are ignored and relative photometric zero-points not calculated. This may be useful if the relative dither offsets between exposures are known to be precisely reflected in the headers.

6.3.5. An Astrometric Challenge: AO Images

Current astrometric reference catalogs (e.g., USNO, 2MASS) are mostly based on plate scans or wide-field images with an angular resolution on the order of 1″–2″. This is about 3–5 times lower than the resolution of typical seeing-limited images, and does not pose a problem as long as fields are not very crowded. However, the limit is reached with adaptive optics (AO) systems such as \texttt{GeMS/GSAOI}@Gemini (McGregor et al. 2004) and similar instrumentation at future extremely large telescopes. The pixel scale of GSAOI is 0′′0197, 50 times smaller than the resolution element of the Digitized Sky Survey. Hence the source density of the plate scans becomes too low for successful catalog matching. Resolved multiple sources in the AO data introduce ambiguities, complicating the matching process further. The fields of view of current multi-conjugated AO (MCAO) systems are on the order of 1′, and thus of the same size or smaller than many of the prominent science targets that will be revisited with these instruments. A global astrometric calibration of such data requires high resolution (and possibly much deeper) secondary catalogs obtained from images taken with 2–8m class telescopes.

Figure 7 of globular cluster NGC 1851 illustrates the aforementioned challenges. The high source density in this field required a staggered approach. For the successful astrometry of the GSAOI data a tertiary catalog had to be used, which was obtained from a high resolution $K_s$-band HAWK-I@VLT image. This, in turn, could not be calibrated with USNO-B1.
(no detections within the cluster) or 2MASS (too shallow in the outskirts and too few detections within the cluster). Instead, a reference catalog was extracted from an optical wide field image taken with WFI at the 2.2 m MPG/ESO telescope, which itself was matched against 2MASS. At the other extreme we find observations of extragalactic targets, where hardly any reference sources are available in the common catalogs within a 1’ radius. Deep classical observations in good seeing are thus required to provide a secondary standard star catalog.

7. SKY SUBTRACTION

The main objective of sky subtraction is to achieve a homogeneous zero background level across the FP. At this point THELI assumes that any background variations are additive and hence must be subtracted, i.e., that the photometric zero-point is already uniform.

Sky subtraction is essential for multi-chip cameras. Consider two different pixels in a coadded image, constructed from \( n \) dithered exposures without sky subtraction. While all \( n \) exposures contribute to the first coadded pixel, the second pixel may lack data points due to detector gaps. If the background level varies between exposures, then their mean (or median) values at the position of the two coadded pixels will be different. Consequently, chip gaps will show up as discrete brighter or darker areas in the coadded image without prior sky subtraction.

Difficulties arise for crowded fields or extended objects (with faint halos), where local and unbiased background measurements are difficult. Gradients caused by, e.g., zodiacal light or the moon cause further complications. These can be controlled earlier on with separate sky exposures (see Section 4), and/or with the following two options for individual sky subtraction.

7.1. Full Modeling

For sparse fields and fields without extended objects, full background modeling can be done. The process is similar to what is described in E05, with some modifications. SExtractor is used to mask objects with adjustable detection thresholds. To some degree a faint extended halo can be masked, as long as the amplitude of the background variations is smaller than that of the halo. The masked areas are interpolated iteratively, based on the values of non-masked pixels in the local neighborhood. In this way background variations are reflected properly across larger masks, where a single constant estimate is insufficient. The resulting image, free of objects, is then convolved with a Gaussian kernel yielding the final sky model. Ideally, the kernel’s FWHM is equal to or smaller than the typical extent of the background variations yet large enough that the filter remains insensitive to extended sources.

7.2. Subtracting a Constant Value

Background modeling on individual images is not an option whenever surface photometry or detection of faint extended structures is required. This holds in particular if the structures are not visible in individual images. Intra-cluster light, tidal features, and faint halos around brighter objects are good examples of when background model is not an option (Da Rocha et al. 2008; Tziamtzis et al. 2009; Martínez-Delgado et al. 2010; Guennou et al. 2012). To preserve the faint structures a constant sky must be subtracted.

In THELI a constant background value can be determined individually for each chip of a detector mosaic using various statistical estimators. Alternatively, a particular chip unaffected by the extended object can be used to estimate the sky level for all other chips. The measurement is performed either from the entire chip or from a sub-area, and after object masking has taken place (Section 7.1). Sub-areas can be defined using pixel coordinates and are thus fixed to the detector, or by sky coordinates such that the measurement box moves with the dither pattern. The latter is useful for crowded fields, allowing the background to be measured repeatedly and precisely from the same location. Note that this (alternative) requires the Update header function to have been applied after the successful calculation of an astrometric solution (Section 6.3).

Should even more flexibility be required, the constant background values determined can be adjusted manually for individual chips or entire mosaic until the coaddition is satisfactory.

8. COADDITION

During the image coaddition phase the user can choose between the following SWarp parameters:

1. Celestial coordinate systems (equatorial, galactic, ecliptic, supergalactic),
2. WCS projections (TAN, COE, ...),
3. Combine types (weighted mean, median, ...),
4. Resampling kernels, and
5. Output pixel scale.

For multi-color data sets it is recommended that one use identical reference coordinates (R.A., decl.) for the sky projection. A particular object will then end up on precisely the same pixel in the coadded images of all different filters (see Appendix C.6). For non-equatorial coordinate systems, the corresponding counterparts must be used, e.g., galactic longitude and latitude.

8.1. Filtering and Arbitrary Sky Position Angles

In the first step, SWarp gets a list of all images to stack and creates a FITS header for the coadded image. At this level the user can decide which exposures enter the coaddition process, be it a selection by filter (if a multi-color data set is present), seeing, and/or relative photometric zero-point. For multi-chip cameras a selection of chips can also be made, resulting in only part of the mosaic being created.

Two additional options act directly on the header of the coadded image before it is created. In the case of wide-angle and all-sky projections it is difficult to predict the geometry of the coadded image, resulting in truncation. In this case the output size (NAXIS1/2) can be corrected. The other option is to choose an arbitrary sky position angle since SWarp orients all stacked images with north up and east to the left by default. This is done by updating the CD-matrix, and increasing the image geometry to accommodate the new layout.

8.1.1. Outlier Rejection

In the second step, SWarp resamples the individual images, normally followed by the coaddition. SWarp does not, however, offer outlier rejection during stacking. While a median filter may be used to reject outliers during coaddition, its variance is a factor of \( \sim \pi/2 \) higher compared to a mean combination (assuming Gaussian noise in the input images, see Section 3.13 of Kaiser 2002). The effective exposure time would need to be increased by a similar factor to compensate for this loss of sensitivity. THELI therefore offers the option of reconstructing the stacks for each coadded pixel based...
on the resampled images, identifying bad pixels by running a \(\sigma\)-clipping algorithm. Spurious pixels then have their weight set to zero in the resampled weight images. In this way, photometric integrity is preserved while still using the weighted combination.

If a pixel is found to be bad, it may be masked only if the \(k\) neighboring pixels are also bad (bad pixel cluster size). This accounts for the fact that most resampling kernels distribute the flux of one input pixel over several output pixels. In addition, if a pixel is located \(m\) pixels or less from a bad pixel, it can also be masked. This is useful for the complete masking of bright asteroids or satellites, whose faint wings caused by the point-spread function go undetected by the outlier rejection.

8.1.2. Locking onto Proper Motion Targets

The proper motion vector of solar system objects can be projected onto the headers of the resampled images before final coaddition by adjusting the CRVAL1/2 keywords. The coadded image then follows the moving target whereas stars appear trailed. In this manner, most moving objects, which are possibly invisible in single images, can be analyzed provided their proper motions are known or can be guessed. The DATE-OBS keyword must be present in the input headers for sufficiently accurate timing. Currently, only linear proper motion vectors are supported while second-order effects are ignored. Figure 8 shows an example image.

8.1.3. Edge Smoothing

In some cases it is not possible to achieve good sky subtraction, resulting in small discontinuous jumps at chip boundaries. This can be problematic for surface photometry or feature detection, in particular if the jump runs across the target. The discontinuity can be suppressed by edge smoothing, where the edges of the weight images are softened with a sine function of wavelength \(\lambda\) prior to resampling. Pixels at the outermost edge of the weight map are assigned a value of zero, corresponding to the minimum of the sine function. The pixel values then gradually increase inward until they reach their original value after \(0.5\lambda\) (maximum of the sine function). Within this border the weight maps are unchanged. The second derivatives at the transition points are zero. The chosen edge smoothing length, \(0.5\lambda\), should be similar or a bit smaller than the size of the dither pattern. Photometry is conserved since this method is applied only to the weight maps. The noise level along the chip boundaries is increased by this process due to the lower weight.

9. SUMMARY AND OUTLOOK

In this paper I have presented an overview of the THELI data reduction pipeline. THELI integrates a large range of tools and offers them in a homogeneous and convenient manner for end-to-end processing. Many different instruments at various observatories are pre-configured and their data are easily reduced. A short learning curve ensures quick success for new and more seasoned observers alike. The great flexibility facilitates a broad range of scientific studies as demonstrated by, e.g., Meech et al. (2005), Santander-García et al. (2008), Lieder et al. (2012), McMichael & Bentley (2012), Gentile et al. (2013), and Lane et al. (2013).

The development of THELI continues, as both astronomical instrumentation and software are highly dynamic areas. One of the main work areas, as already mentioned, is a port to the newer Qt\(\pm\)5 library ensuring cross-platform compatibility and the latest standard in GUI development. This next major release will also include automatic satellite detection and a method for 2D illumination correction (see Section 4). On the instrumental side, the focus is on mid-IR cameras and further support for instruments and observatories that are not yet included.

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APPENDIX A

OPTICAL EXAMPLE: VLT/FORS1

This section introduces the basic reduction steps with THELI, using a set of raw data taken from the ESO archive.\textsuperscript{11} The idea

\textsuperscript{11} http://archive.eso.org/eso/eso_archive_main.html
is to provide the beginner with a simple data set and a sense for how THELI works. Only mandatory steps are covered, i.e., preparation of the data, the main calibration, weighting, astrometry, sky subtraction, and coaddition. The example is based on the small R-band FORS1@VLT data set listed in Table 1 and taken by Sekiguchi et al. (2002) for TNO 1996 TO66 (Figure 8). At that time FORS1 was a single-chip camera.

A.1. Initializing THELI and Preparing the Data

Sort the uncompressed data into three arbitrarily named sub-directories, BIAS, FLAT, and SCIENCE, which share the same parent directory /MAINPATH. Next, in THELI’s Initialise section,

1. enter a project name (e.g., FORS1 DEMO),
2. select the number of CPUs you want to use,
3. select FORS1_1CCD@VLT from the instrument list, and
4. let THELI know the directory tree (Figure 1).

In the Preparation section, mark the Split FITS/correct header task and launch it by clicking on Start. THELI will cycle through the three data directories, split multi-extension FITS files into single FITS files (if applicable), and translate the FITS headers (Section 3.1). File names will end in _i.fits, where i will run from 1 to n for a multi-chip camera with n detectors.

### Table 1
Small FORS1@VLT Data Set for the Example in Appendix A

| File Name                  |
|----------------------------|
| BIAS                       |
| FORS.1999-11-14T11:35:16.464.fits |
| FORS.1999-11-14T11:36:02.607.fits |
| FORS.1999-11-14T11:36:49.109.fits |
| FORS.1999-11-14T11:37:35.510.fits |
| FORS.1999-11-14T11:38:22.303.fits |
| FLAT                       |
| FORS.1999-11-13T23:42:09.117.fits |
| FORS.1999-11-13T23:43:21.663.fits |
| FORS.1999-11-13T23:44:40.835.fits |
| FORS.1999-11-14T09:17:20.006.fits |
| FORS.1999-11-14T09:18:14.457.fits |
| SCIENCE                    |
| FORS.1999-11-14T00:26:52.043.fits |
| FORS.1999-11-14T00:38:56.322.fits |
| FORS.1999-11-14T00:51:18.793.fits |
| FORS.1999-11-14T01:03:58.970.fits |
| FORS.1999-11-14T01:16:04.471.fits |
| FORS.1999-11-14T01:28:27.545.fits |
| FORS.1999-11-14T01:45:37.796.fits |
| FORS.1999-11-14T01:57:40.224.fits |
| FORS.1999-11-14T02:10:04.102.fits |
| FORS.1999-11-14T02:27:48.341.fits |

**Notes.** Exposures can be identified in the ESO raw science archive by selecting FORS1 as the instrument, entering “13 11 1999” for the night, and by limiting the maximum number of output rows to 200.

A.2. Calibration

Mark Process biases, Process flats, and Calibrate data. This creates the master bias and the bias-corrected master flat, /MAINPATH/BIAS/BIAS_1.fits, /MAINPATH/FLAT/FLAT_1.fits, and applies both to the science data. All files are also overscan-corrected and trimmed. The tasks can be executed individually or in one go. File names in SCIENCE will now end in _10FC.fits, where the status string 0FC indicates that the exposures have run through this pre-processing stage. Other steps at a later stage, such as background modeling, append more characters to the status string, but they are not required here.

A.3. Weighting

The global weight is a copy of the normalized flat field, where static bad pixels can optionally be zeroed (Section 5). It forms the basis for the individual weight maps. All weight images can be found in /MAINDIR/WEIGHTS.

Mark Create global weights and Create WEIGHTs and run both tasks with their default configuration settings. The global weight maps should be inspected for excessive masking if tighter lower and upper thresholds are chosen for the normalized flat.

A.4. Astrometry and Relative Photometry

First, we need to download the astrometric reference catalog. Select SDSS-DR9 and a magnitude limit of 23, so we get sufficiently many sources matching the VLT data. The search radius is automatically adjusted to 5’. Click on Get catalog to download nearly 500 reference sources. Then run Create source cat with its default parameters, which creates the binary catalogs for each exposure in /MAINPATH/SCIENCE/cat. Therein you will also find ds9cat and skycat sub-directories, containing catalogs formatted for overlay in these two FITS viewing programs. Two versions of the astrometric reference catalog, called ds9cat/theli_mystd.reg and skycat/theli_mystd.skycat, are kept there as well.

Now run the astrometry. Mark Astro+photometry, select Scamp from the pull-down menu next to the task, and click on Configure. The default settings work with a broad range of data. Click on Defaults (this page) to make sure no different values from a previous run are loaded. Close the configuration dialog, and start the astrometry task. Once done, the sub-directory /MAINPATH/SCIENCE/plots contains the Scamp check plots which you should inspect.12 The most important ones are

1. fgroups_1.png: The exposures’ layout on sky. Green (red) marks indicate objects in the reference catalog that were (were not) matched by an object in the exposures. You should recognize the dither pattern. The image frames displayed should not appear sheared or distorted, and you should recognize the dither pattern.
2. distort_1.png: The optical distortion, encoded as a change of pixel scale across the field. This should be circularly symmetric and aligned with the optical axis of the telescope (usually at the center of the detector array).
3. astr_referror_1.png: The astrometric residuals with respect to the reference catalog. No systematic trends should be visible, and the scattering should represent the astrometric uncertainties of the reference catalog.

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12 A large selection of good and bad Scamp check plots is shown in the online user manual.
4. **astr_intererror.1.png**: The internal astrometric residuals, i.e., the accuracy exposures were registered with respect to each other. This should be on the order of 1/5th to 1/15th of a pixel, and systematic trends should be absent.

**A.5. Sky Subtraction and Coaddition**

No extended sources are present, therefore normal sky modeling is adequate. In the Coaddition section, enter the configuration for sky subtraction, select Model the sky and load the default parameters. Exit the dialog then mark and run the Sky subtraction task. The names of the sky-subtracted images end in `_10FCB.sub.fits`.

Lastly, perform the image coaddition with the default parameter configuration. If you want, enter a proper motion vector of ∆RA = −1.531915 hr⁻¹ and ∆DEC = −0.59283 hr⁻¹ to register the exposures on the TNO, reproducing Figure 8. Enter an extra Identification string so that a previous coaddition without proper motion is not overwritten. Exit the configuration dialog and run the task. The final coadded image and weight can be found in the original image list, the masks are simply links to the coadded images. The background models for each individual frame from which the background model was calculated. Since we chose to not detect objects, the masks are simply links to the masked data. The background models for each individual frame can be found in the original image list.

**APPENDIX B**

**NEAR-IR EXAMPLE: HAWK-I@VLT**

This example is based on H-band observations of low mass objects in the σ Orionis cluster (Peña Ramírez et al. 2011). The necessary reduction steps for near-IR data are shown, focusing on the background modeling. The latter can be configured in different ways, hence only the settings relevant for this data set are explained. Since HAWK-I@VLT consists of four HAWK-I detectors, this example also explains how astrometry is calculated. In Appendix A are not repeated here unless their importance is to be emphasized.

**B.1. Initializing THELI and Preparing the Data**

Sort the uncompressed data into sub-directories FLAT, FLAT_OFF, and SCIENCE, sharing the same parent directory MAINPATH. Choose a new project name, e.g., HAWKI_DEMO, select HAWKI@VLT in the instrument list, and make the directory tree known to THELI.

In the Preparation section, mark the `Split FITS/correct header` task. This file name will end in `_i.fits`, where `i` runs from 1 to 4, representing the four chips of HAWK-I.

**B.2. Calibration**

First, set the Do not apply BIAS/DARK check box as the pre-read is already subtracted from near-IR data. Run Process flats to create combined bright and dark flats. The bright flat will have the dark flat subtracted automatically. If you do not want to subtract a dark flat, just do not provide that data. Next, run Calibrate data to apply the flat field to the science images.

**B.3. Background Modeling**

Now a background model has to be removed, a task inevitable with near-IR data. This is done in the Background section. First of all, we have to decide whether we want a one-pass or a two-pass background model. In most cases a two-pass approach is required, unless the field is empty, exposures were frequently and widely dithered, and/or accurate photometry is not necessary. Our field has several bright stars and may contain nebulosity. A two-pass strategy is therefore adequate, meaning the same task is run twice, the second time with fine-tuned parameters.

**B.3.1. First Pass of the Background Model**

Open the configuration for Background model correction. You will be presented with the following settings.

1. **Mask objects.** For the first pass, remove the default entries for DT and DMIN, representing the SExtractor DETECT.THRESH and DETECT.MINAREA parameters. This will create a quick and simple background model without prior object masking. Select the Median combination, and switch off the SExtractor filtering.

2. **Reject pixels from the stack.** By default, the highest pixel in the stack is rejected prior to stack combination. Accept this setting. You may want to increase this number if you create larger static stacks, have high source density, and/or larger dynamic window sizes.

3. **How to apply the background model.** Different options are available. For near-IR data we subtract the model and leave the two smoothing scales empty. We want to `rescale` the model to take out any temporal global intensity variations. We do not apply the model to SKY data (because we do not have SKY exposures in this example), and we also do not adjust the gains between chips (done during flat-fielding).

4. **Static or dynamic model.** Choose a window size of 6, and accept the default value for the maximum gap size (1.0h; there is no gap in this exposure sequence if the same exposures as listed in Table 2 are used).

Once finished, the files will have the string OFCB in their names. The previous OFC images are parked in OFC/Images, and a MASK/Images sub-directory contains the object masks from which the background model was calculated. Since we chose to not detect objects, the masks are simply links to the unmasked data. The background models for each individual frame can be found in the BACKGROUND directory.

In case horizontal or vertical gradients from a reset anomaly are still present (as in Figure 4), one should now run the Collapse correction task (Section 4.2). This is not necessary for the present data.

**B.3.2. Second Pass of the Background Model**

At this point the images are mostly flat, revealing fainter objects (which can thus be masked). To create an improved background model we simply repeat the task with modified parameters DT=1.5 and DMIN=10.

THELI will recognize that this is the second pass. Objects detected in the OFCB images will be masked in the OFC images (parked in OFC/Images), and the improved masks can be found again under MASK/Images. The temporary OFCB images from the 1st pass will be moved to OFC/Images/1PASS, and the original OFC images are restored. Improved background models are calculated and applied, resulting in the final set of OFCB images.
Inspect a few of the masks and the resulting OFCB exposures, in particular a few at the beginning, the middle, and at the end of the sequence. Relax DT = 1.5 if excessive masking is recognized, and simply re-run the task. In general, two passes are sufficient. One without any detection thresholds (faster), and the second one with correctly chosen settings. If necessary, a collapse correction can be applied afterwards.

### B.3.3. Separate Sky Exposures

If extended sources were present in these HAWK-I data, then the background model could not be calculated from the data themselves. Instead, separate exposures of a nearby blank field would be needed. They have to be collected in a SKY directory (Section 4.1.1), where THELI would find and automatically process them. This is not the case for this example, but I include it here as it is a common procedure.

In the following, the letter “O” denotes an object exposure and the letter “S” a sky exposure. For example, alternating sequences could be

1. 00000--SSSSS
2. 000--SSS000--SSS...
3. 00-S00-S00-S...

The first one would be chosen for a short observation of a brighter target, justifying a static background model. The other sequences could also be processed with a single static model, but the layout suggests that the observer wanted to keep track of the sky variations, calling for a dynamic model. The layout of the sequences does not matter to THELI. You simply collect all sky exposures in a separate SKY directory. For the dynamic model, THELI will identify the closest sky exposures in time for a given object exposure, based on the window size, and assuming that a valid (modified) Julian date MJD-DBS is present in the FITS headers. The latter should be the case for all predefined instruments in THELI, but you may want to check, as the raw FITS headers may have changed or been corrupted.

#### B.4. Weighting

Weighting is essentially the same as for optical data. Tighter thresholds should be chosen for the normalized flat to remove spurious pixel clusters. Set the min and max values for FLAT_norm to 0.9 and 1.1, respectively, and check the WEIGHT/globalweight_i.fits images for excessive masking.

#### B.5. Astrometry and Relative Photometry

For the reference catalog we choose again SDSS-DR9 and a magnitude limit of 23, which will result in about 800 reference sources. For a field with high extinction 2MASS could be a better choice to maximize the overlap between reference and source catalogs. Create source cat can be run with its default parameters. For sparser fields than this example, DT can be lowered from 5 to about 1.5 to get sufficiently many objects.

Use Scamp for the astrometry, and select the default configuration parameters as for the first example. However, set MOSAIC_TYPE = SAME_CRVAL as we are processing data from a multi-chip camera. A focal plane (FP) model that has been determined previously based on observations of a dense stellar field will then form the basis of the final astrometric solution. This covers relative chip positions and rotations, as well as the CD-matrix. Even sparse fields with only few detections per chip can thus be solved. A prior distortion model, however, cannot be loaded by current versions of Scamp. The distortion is determined by Scamp from the dithered data themselves.

All pre-configured multi-chip instruments in THELI have their FPs already determined in this manner. It may happen that these default FPs need to be updated, e.g., after a dead detector has been replaced, the optics re-aligned, or if the quality of the astrometric solution is insufficient. In these cases you can create a new FP from a different stellar field taken more recently, or simply from the current data set itself. To create a new FP, set FOCAL_PLANE = Create new FP, otherwise leave the default setting Use default FP.

#### B.6. Sky Subtraction and Coaddition

In Section B.3 a dynamic background model was subtracted yet small constant non-zero offsets on the order of half a percent of the original background level may still be present in the images together with spatial variations of similar amplitude if the atmosphere was particularly unstable. Running an individual sky background model as shown for the optical example suppresses these residuals to a level of \( \sim -0.1\% \) or less. Alternatively, you can choose a constant sky subtraction.

The coaddition can be performed with default parameters.

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15 The prior CD-matrix will override the CD-matrix values from the FITS headers. If the position angle of your observations is different from the FP by more than PPOSANGLE_MAXERR, then the matching with the reference catalog will fail. Simply set PPOSANGLE_MAXERR = 180 to allow for all position angles to be searched.
APPENDIX C

MID-IR EXAMPLE: T-ReCS@GEMINI

This example is based on multi-band observations of the circumnuclear starburst ring in NGC 7552, (Appendix C; PI: B. Rodgers), and shown in Figure 5. The data can be obtained from the Gemini Science Archive. T-ReCS is a highly sensitive mid-IR imaging spectrograph and was offered at Gemini-South until 2012. This example highlights the typical chop-nod process for ground-based mid-IR observations, the special requirements for astrometry, and THELI’s general support for multi-color data sets during coaddition.

C.1. Initializing THELI and Preparing the Data

T-ReCS images (and those of other mid-IR cameras) are usually not flat-fielded due to the highly variable mid-IR background. Likewise, a bias or dark subtraction is unnecessary as it is taken care of automatically by the pairwise image subtraction. Therefore, all images listed in Table 3 may be copied into the same SCIENCE directory. Choose a new project name, e.g., NGC7552_MIR, select TReCS@GEMINI, and make the directory tree known to THELI.

In the Preparation section, mark the Split FITS/correct header task, and check the Split MIR cubes option. Contrary to optical and near-IR data, several additional observations take place for T-ReCS. First, THELI checks whether the images were taken in full chop-nod mode, which is the case for almost all exposures with T-ReCS (and currently the only supported mode for this camera). The images used in this example typically contain eight to nine extensions with a full chop-nod cycle. THELI will perform the chop-nod sky subtraction and write out separate images per cycle, as we asked to split the cubes. If the target was very faint and only visible in the stacked cube, then the splitting option should not be checked, as otherwise the astrometry will become unfeasible.

C.2. Calibration

As mentioned above, no dark or flat correction is done. Most of the sky and telescope background was already removed in the previous step. Nevertheless, the calibration task has to be run for compatibility reasons, otherwise the data will not propagate properly through THELI. Simply set the Do not apply BIAS/DARK and Do not apply FLAT check boxes, and run Calibrate data. The latter will merely insert the standard 0PC string into the file names and set some internal processing flags.

### Table 3

| File Name               | Bandpass     |
|-------------------------|--------------|
| S20110722S0134.fits     | [Si II] 8.8 μm |
| S20110722S0135.fits     | [Si II] 8.8 μm |
| S20110722S0136.fits     | [Ne II] 12.8 μm |
| S20110722S0137.fits     | [Ne II] 12.8 μm |
| S20110722S0138.fits     | [Ne II] 13.1 μm |
| S20110722S0139.fits     | [Ne II] 13.1 μm |
| S20110726S0086.fits     | Qa 18.3 μm    |
| S20110726S0087.fits     | Qa 18.3 μm    |

**Notes.** The exposures can be found in the Gemini Science Archive, by entering NGC 7552 for the object, and T-ReCS for the instrument.

C.3. Collapse Correction

The chop-nod background correction for mid-IR depends strongly on the atmosphere’s precipitable water vapor and possible cirrus. Observations are only possible in dry and clear conditions, in particular in the Q bandpass centered on 20 μm. Chop-nod cycles taken in unstable conditions may show strong background residuals and should be discarded. This is why THELI does not automatically combine all cycles during splitting, but leaves them for individual inspection so that bad exposures can be discarded manually.

For this example data set no images have to be rejected. However, you may notice that a small vertical gradient exists in some of the data. This can be easily corrected for using the Collapse correction. Adopt the default configuration values (leave DT and DM IN empty), with x as the collapse correction. We want to exclude the entire extended and diffuse object from the modeling, defining the vertices of the excluded region as xmin=110, xmax=220, ymin=50, and ymax=160. This is for the [Si ii] 8.8 μm, [Ne ii] 12.8 μm, and [Ne ii] 13.1 μm filters. The observations in the Qa 18.3 μm bandpass are significantly offset and require xmin=130, xmax=240, ymin=70, and ymax=180. To achieve this, park the Qa exposures in a temporary directory and run the collapse correction with the first setting on the [Si ii] and [Ne ii] exposures. Then exchange the images in the current and the temporary directory, and apply the collapse correction to the Qa exposures with the updated exclusion region. After that, merge all images again in the SCIENCE directory.

C.4. Weighting

As no flat field is available, the individual weights are based on constant global weights with value unity. Select Same weight for all pixels in the configuration of Create global weights. The individual weights can be created with default settings, i.e., cosmetics, hot pixels, and obvious static pixel defects will be masked.

C.5. Astrometry and Photometry

Mid-IR images probe a vastly different part of the spectrum than optical or near-IR images and typically only one or two compact sources or diffuse emission are seen. Matching with common astrometric reference catalogs, a full distortion correction, and/or the WCS solution is in general not possible. Usually, a simple linear registration of images is sufficient. The global WCS in the final coadded image will be limited by the accuracy of the WCS in the FITS raw data, and may have to be adjusted by hand if necessary.

Two possibilities exist for mid-IR data. In case of a single point source, the simple Shift (float) approach can be used, requiring the creation of source catalogs as discussed in the previous examples. This approach does not work here, as one or several point sources may be detected in the individual images, together with extended flux. The number of sources is very small hence an unambiguous cross-identification of exposures is unlikely. Imagine you have one image with one source detected and another one with two sources. Without further prior information, such as assumptions about the accuracy of the WCS in the header, it is not possible to register these two images automatically. Use the cross-correlation method (Xcorr) instead. It will run SExtractor with fixed low detection thresholds to create images containing compact and extended source flux only. These are then cross-correlated, yielding the relative offsets.
Table 4
Pre-configured Optical Imagers

| Instrument@Telescope | No. of Detectors | Comment |
|----------------------|-----------------|---------|
| ACAM@WHT             | 1               |         |
| ALFOSC@NOT           | 1               |         |
| ALTA16M@VYSOS06      | 1               |         |
| AhaU2@ASV            | 1               |         |
| CFH12K@CFHT          | 12              |         |
| DECam@CTIO           | 62              |         |
| EFOSC2@ESO3.6m       | 1               | 1 × 1 and 2 × 2 binning |
| EMMI@NTT             | 1               | BIMG and RILD imaging modes |
| ENZIAN_CAS@HOLI_1M   | 1               |         |
| FORSI@VLT            | 1               | Old and new configuration with 1 and 2 CCDs, respectively |
| FORS2@VLT            | 1               | Old and new configuration with 1 and 2 CCDs, respectively |
| GEMINI-NORTH         | 3               | 1 × 1 and 2 × 2 binning |
| GOODMAN@SOAR         | 1               | 1 × 1 and 2 × 2 binning |
| GPC1@PSI             | 64              |         |
| IMACS_F@LCO          | 8               | Old and new detector configuration |
| IMACS_F4@LCO         | 8               | Old and new detector configuration |
| LAICA_2x2@CAHA       | 4               | 1 × 1 and 2 × 2 binning |
| LBC@LBT              | 4               | BLUE and RED cameras |
| LDSS3@LCO            | 2               |         |
| LORRI@NewHorizons    | 1               |         |
| MEGACAM@LCO          | 36              | 2 × 2 binning only |
| MEGAPRIME@CFHT       | 36              | Support for raw and ELIXIR pre-processed data |
| MEROPA@MERCATOR      | 1               |         |
| MOSAIC-I0@KPNO_0.9m  | 8               | Old configuration (before 2010 Aug) |
| MOSAIC-I0@KPNO_4.0m  | 8               | Old configuration (before 2010 Aug) |
| MOSAIC-II@CTIO       | 8               | 8- and 16-channel mode, before and after fix of dead readout port |
| MOSCA_2x2@NOT        | 4               | 2 × 2 binning only |
| OASIS4x4@WH          | 1               | 1 × 1 and 4 × 4 binning |
| OMEGACAM@VST         | 32              |         |
| PFC2@WH              | 2               |         |
| SDSS                 | 1               | For SDSS images directly downloaded from the server |
| SOI@SOAR             | 2               |         |
| SuprimeCam_OLD@SUBARU| 10              | Before and after 2001 Apr (replacement of dead CCD) |
| SuprimeCam_NEW@SUBARU| 10              | Installed 2008 Aug; Support for raw and SDFRED pre-processed data |
| SuSi2_2x2@NOT        | 2               | 2 × 2 binning only |
| VIMOS@VLT            | 4               |         |
| WFC@INT              | 4               | 1 × 1 and 2 × 2 binning |
| WFI@AAT              | 8               |         |
| WFI@SSO_40inch       | 7               |         |
| WFI@MPGESO           | 8               |         |
| Y4Kcam@CTIO          | 1               |         |

C.6. Sky Subtraction and Coaddition

After collapse correction, the mean sky background level is zero, therefore sky subtraction can be skipped. If the collapse correction was not done, the images may still show some constant offset which can be removed using the Mode in Subtract a constant sky.

Coaddition is performed with default settings. However, since we have observations in four different bands present in the same directory, we want the final coadded images to have identical geometries. We also want the same physical object to appear in the same pixel. This is achieved as follows:

1. First, find the R.A. and decl. values of the center of your image. It does not need to be accurate, but if you are too far off, the coadded image could be truncated. Enter these values as Ref RA|DEC in the configuration of the Coaddition dialog. For this example we use RA=23:16:10.6 and DEC=-42:35:04. By using the same values for the coaddition of all four bands, we enforce an identical astrometric deprojection needed for automatic image registration later.

2. Coadd this filter. In this pull-down menu THELI presents a list of the four bands available in the SCIENCE directory. Start with the first one, Ne II-12.8μm, which will create a coadd_Ne II-12.8μm directory containing the corresponding coadded image.

3. Optionally, you can choose an additional outlier rejection by setting threshold=3 and cluster size=4

At this point, four coadd.<filter> directories are present, with the stacked images and their weights, coadd.<weight>.fits. While these have identical values of CRVAL and CRPIX, their geometries are still different due to initial pointing variations, chop-nod offsets etc. To register the images, go to the main menu at the top of the THELI window, and open Miscellaneous → Prepare color picture. You will be presented with a list of all coadd.<filter> directories. Select the ones you are
Table 5
Pre-configured Near- and Mid-IR Imagers

| Instrument@Telescope          | No. of Detectors | Comment                                |
|------------------------------|-----------------|----------------------------------------|
| FLAMINGOS2@GEMINI-SOUTH      | 1               |                                        |
| FourStar@LCO                 | 4               |                                        |
| GROND_IRIM@MPGESO            | 1               |                                        |
| GSAOI@GEMINI-SOUTH           | 4               |                                        |
| HAWKI@VLT                    | 4               |                                        |
| INGRID@WHT                   | 1               | Normal imaging and polarimetry mode    |
| ISAAC@VLT                    | 1               |                                        |
| LIRIS@WHT                    | 1               |                                        |
| MMIRS@LCO                    | 1               |                                        |
| MOIRCS@SUBARU                | 4               |                                        |
| NACOSDI@VLT                  | 1               |                                        |
| NEWFIRM@CTIO                 | 4               |                                        |
| NICS@TNG                     | 1               |                                        |
| NICI@GEMINI-SOUTH            | 2               |                                        |
| NIRI@GEMINI-NORTH            | 1               |                                        |
| NOTcam@NOT                   | 1               | High and low resolution modes          |
| Omega2000@CAHA               | 1               | High and low resolution modes          |
| OSIRIS@SOAR                  | 1               |                                        |
| PISCES@LBT                   | 1               |                                        |
| SOFI@NTT                     | 1               |                                        |
| SPARTAN@SOAR                 | 4               | Mid-infrared                           |
| TREC@GEMINI                  | 4               | Mid-infrared                           |
| VIRCAM@VISTA                 | 16              |                                        |
| VISIR@VLT                    | 1               | Mid-infrared                           |
| WIRCam@CFHT                  | 4               |                                        |

interested in, and then click on Get coadded images. This will create a SCIENCE/color_theli directory, containing the coadded images registered and trimmed to their maximum common overlap, and called <filter>_cropped.[weight].fits. Note that since THELI enforces integer values for the CRPIX header keywords during coaddition, excess pixels can simply be removed and no second resampling has to take place that would degrade image quality.

This approach works for any other multi-color data set. The only requirement is that identical reference R.A. and decl. values are used for the coadditions of the different bands, and that the final coadd_<ID> directories are collected in the same SCIENCE directory.

APPENDIX D
CURRENTLY SUPPORTED INSTRUMENTS

Tables 4 and 5 list the optical and infrared instruments currently supported by THELI.

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