Introduction
The future Earth science missions at the National Aeronautics and Space Administration (NASA) promise to provide an explosion of data and a platform for science that previously was unachievable using existing hardware, software, and assets. Instrument resolution is increasing, as is the ability of software and hardware to deal with data volumes that will easily grow to the 10–100 petabyte range in the next five years [1]. Over the past twenty years, NASA has invested in software to support all phases of the Earth science mission pipeline. These investments include components and architectures that support science data processing at Science Investigator-led Processing Systems (SIPS), data archival and dissemination at the Distributed Active Archive Centers (DAACs), and ad-hoc data analyses and custom product generation using DAAC-provided data [2]. This general flow is shown in Fig. 1.

For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) Data Processing System (MODAPS) has evolved over time to support higher data processing rates and the production of data products for additional Earth-observing instruments by enhancing its architecture [3]. In addition, several recent efforts [4] to standardize process management and control for both the Orbiting Carbon Observatory (OCO) missions, as well as the NPOESS Preparatory Project (NPP) joint NASA–NOAA–DOD missions, have also demonstrated the utility in the reuse of software assets.

However, to date the aforementioned efforts...
science data system components and architectural patterns are reconstructed for each mission. There have been a number of reasons for this practice including: (1) the distributed scientific expertise of NASA, (2) the desire to have that expertise co-located with the data as it is processed and delivered for wide dissemination, (3) procurement practices, where contract and equipment resources are stove-piped into separate contracts and programs, and (4) each scientific community purports a unique set of requirements for data processing and data products, that may not easily lend itself to justify reuse.

The paradigm of NASA missions is changing, primarily due to the upcoming missions identified in the National Research Council’s Earth Science and Applications from Space decadal survey [5] (as well as other future “decadal-like” missions). It is even more imperative that NASA look to reduce costs, increase software productivity, explore areas for consolidation of homogeneous services, and ultimately promote and facilitate a culture of reusing successful software assets and patterns across its missions.

Software reuse can help inform the successful design of future NASA missions in a number of different ways, in particular through: (1) identification and selection of existing, proven Earth science software components (or software components applicable in Earth science data systems) whose reuse saves development costs and time, (2) application of existing architectural styles and patterns [6] that induce specific quality attributes (reliability, scalability, etc.) in the resultant software, and (3) identification of new assets developed for missions which are of broader applicability, and themselves should be disseminated to the community.

Reusable software artifacts are not limited to just code. These assets may include algorithms and models, architectures and design patterns, systems modules and scripts, technical documentation and test results, and use metrics as well as other artifacts produced during the software development life cycle.

The NASA Earth Science Data Systems (ESDS) Software Reuse Working Group (SRWG) is chartered with the investigation, production, and dissemination of information related to the reuse of NASA Earth science software assets. One major current objective is to engage the NASA decadal missions in areas relevant to software reuse.

In this paper we report on the current status of these activities. First, we provide some background on the SRWG in general and then discuss the group’s flagship recommendation, the NASA Reuse Readiness Levels (RRLs). We continue by describing areas in which mission software may be reused in the context of NASA decadal missions. We conclude the paper with pointers to future directions.

**Working Group Background**

The NASA Earth Science Data Systems (ESDS) Software Reuse Working Group is chartered with the promotion and identification of software assets targeted for reuse in NASA’s Earth Science Data System pipeline [7]. The group is focused on architectures and technologies that facilitate software reuse. In particular, we are investigating software components and architectures developed to enable cloud and grid computing capabilities, as well as cyberinfrastructure for using mission and scientific data.

The flagship product of the group to date is a focused set of NASA Reuse Readiness Levels (RRLs), which have been released and are now available.

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**Table 1. Summary of Reuse Readiness Levels (RRLs)**

<table>
<thead>
<tr>
<th>Level</th>
<th>Summary</th>
</tr>
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<tbody>
<tr>
<td>RRL 1</td>
<td>Limited reusability; the software is not recommended for reuse.</td>
</tr>
<tr>
<td>RRL 2</td>
<td>Initial reusability; software reuse is not practical.</td>
</tr>
<tr>
<td>RRL 3</td>
<td>Basic reusability; the software might be reusable by skilled users at substantial effort, cost, and risk.</td>
</tr>
<tr>
<td>RRL 4</td>
<td>Reuse is possible; the software might be reused by most users with some effort, cost, and risk.</td>
</tr>
<tr>
<td>RRL 5</td>
<td>Reuse is practical; the software could be reused by most users with reasonable cost and risk.</td>
</tr>
<tr>
<td>RRL 6</td>
<td>Software is reusable; the software can be reused by most users although there may be some cost and risk.</td>
</tr>
<tr>
<td>RRL 7</td>
<td>Software is highly reusable; the software can be reused by most users with minimum cost and risk.</td>
</tr>
<tr>
<td>RRL 8</td>
<td>Demonstrated local reusability; the software has been reused by multiple users.</td>
</tr>
<tr>
<td>RRL 9</td>
<td>Demonstrated extensive reusability; the software is being reused by many classes of users over a wide range of systems.</td>
</tr>
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available for use [8]. The RRLs, similar to the NASA Technology Readiness Levels (TRLs) for technology, are a nine-level guide that can be used to rank and compute the reusability of a software asset [9]. A summary of the RRLs, taken from [8], is shown in Table 1.

Besides the RRLs, the Software Reuse Working Group (SRWG) is also working on the development of case study documents describing efforts to leverage the RRLs in the assessment of two areas of NASA mission software: (1) the methodology and suitability of existing NASA software assets for inclusion in a mission, and (2) the identification, curation, and dissemination of software assets that are being developed as part of a NASA mission that can be included in future missions. In addition, the SRWG is working on a recommendation for the packaging of reusable software assets to facilitate distribution, covering an information model for software packaging, and a classification/comparison of the state of the art in software packaging techniques.

Both of the aforementioned documents are considered works-in-progress, and both of the documents include input from current NASA decadal missions, including the Soil Moisture Active & Passive (SMAP) mission and the Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) mission. We also are actively working with other Tier-1 NASA decadal missions including the Orbiting Carbon Observatory-2 mission, and the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) mission to best determine how and where reusable software assets could be leveraged. We plan to support the upcoming Tier-2 missions as they begin to ramp up as well. In the next section we will provide greater detail about the NASA Reuse Readiness Levels (RRLs) and their applicability to NASA decadal missions.

### Reuse Readiness Levels

The NASA Reuse Readiness Levels (RRLs) have been developed for use as a measure to evaluate the potential reusability of software. The RRLs can be used to assess software that is being developed or to assess software assets that are being considered for adoption. Software can be evaluated either by using the RRLs in a simple manner to obtain a rough assessment of the software or by using the RRLs more extensively to obtain a precise assessment, which would include an assessment of the software in terms of nine topic areas.

Using the RRLs in a simple manner, the software under evaluation is compared to the brief summary descriptions of the RRLs to determine a value, from 1 to 9, that reflects the level of the potential reusability of the software. The RRLs can be used in this way to attain a quick assessment, which lacks precision, but may be appropriate for attaining efficient assessments when comparing many competing software candidates or when only a rough estimate of the potential reusability of a software product is required.

Alternatively, extensive use of the RRLs can be applied by using a 9×9 grid to evaluate the software against each of the topic areas to determine the level of maturity that the software has attained for each of the nine topic areas. Using the RRLs in this extensive manner can be more time consuming, but enables assessment of each topic area to identify areas where additional development may be required to meet the needs of a particular software project. Prior to using the RRLs in this manner, the software requirements of the project should be identified for each topic area so that the level of effort necessary to improve the software to an acceptable level for each topic area can be determined.

A calculator is being developed for use with the RRLs (a web-based prototype of this calculator is shown in Fig. 2). Using the RRL
calculator, weights can be established for each
topic area, depending on the importance of a
particular topic area to meet the requirements of
a particular software project, and an average
overall RRL value can be calculated from
assessments of topic area levels. A more
advanced version of the RRL calculator, which
may offer more features and/or guidance on
assessing software assets, is under consideration.
The SRWG has also received a copy of a
Microsoft Excel-based calculator tool, developed
by modifying an existing TRL calculator [10],
from a member of the software reuse
community. We are examining this tool to ensure
that it correctly captures the information
contained in the current release of the RRL
document.

Tools such as the RRL calculator enable a
structured evaluation of reusable assets as
software producers and consumers measure
applicability and compatibility for their
particular project. We are exploring the
integration of the RRL calculator with our Reuse
Enablement System (RES) [11], a software
portal used to track and disseminate information
about reusable software assets. The RES system
is currently being deployed by the Soil Moisture
Active & Passive (SMAP) mission as a proof of
concept as shown in Fig. 3. In the following
section, we will describe the relationship of
RRLs and associated software reuse tools to that
of the NASA decadal missions.

Reuse of Mission Software

The reuse of software offers opportunities for
the new decadal survey missions and future
space missions to reduce costs and improve the
quality of the software that is either produced by
or used from previous efforts. Likewise, software
reuse offers opportunities to obtain similar
benefits when processing and reprocessing data
obtained from such missions. Recipients of the
NASA ESDS Software Reuse Working Group
Peer-Recognition Software Reuse Award [12]
have demonstrated the contribution of new
reusable assets and the utilization of existing
reusable assets in systems development for
NASA missions; for example, the National
Polar-orbiting Operational Environmental
Satellite System Preparatory Project’s Science
Data Segment reused a variety of system
components to reduce development effort and
help ensure reliability [13], as did the Orbiting
Carbon Observatory’s (OCO) Ground Data
System [4].

In conjunction with the ICESat-2 mission
effort, procedures and templates also are being
developed to use the RRLs to assess the current
state of readiness when assessing software from
previous missions for potential reuse in future
missions. Using such tools can help to improve
the usability of software created during previous
missions. Such tools also can be used to assess
the potential reusability of software that is being
developed for new missions to improve its
potential for reusability in other future missions.
The SRWG plans to work with the ICESat-2
team as needed to help them assess some of
the existing software assets from the original ICESat
mission that they plan to reuse.

In addition, using tools, such as calculators (as
shown in Fig. 2), templates, and procedures, in
conjunction with the RRLs, to assess the
reusability of software, can identify aspects of
the RRLs that may be considered for possible
improvement. ICESat-2’s experience will enable
a use case study to help the SRWG improve the
RRLs and how they are used to perform software
reusability assessments. Likewise, testing the use
of such tools for assessing the potential reuse of
software also will contribute to their refinement
and inspire the development of additional tools
for assessing reusability [14, 15, 16] and can
foster the consumer’s confidence that the asset
has been assessed as to its level of robustness
and readiness for operational use.

Conclusions

Considering the data processing needs of the
new decadal survey missions, the reuse of
software from previous missions offers an
opportunity to leverage the investments made in
previous missions. The RRLs have been
developed by the ESDS SRWG to assess the
readiness of software for potential reuse. Using
The RRLs in conjunction with other tools, such as the RRL calculator, templates, procedures, and lessons learned, can improve capabilities for reusing software in new missions and for realizing the benefits of software reuse.

In addition to reusing software and system artifacts from previous missions in the new missions, software reuse offers an opportunity for the decadal survey missions to develop software that can be used in other future missions. Planning for the potential reuse of new software can complement the efforts of reusing previously developed software. Adopting a systematic approach to software reuse can contribute to the improvement of software development practices and to the potential reuse of software and other system artifacts in the future [15].

The use of tools to assess the reusability of software and to register and describe software for potential reuse offers benefits for organizations that develop software for potential reuse and for those that reuse existing software. The use of such tools for the decadal survey missions can assist in the preparation of software that was developed for use in previous missions for possible reuse in future missions. In addition, these tools also can help to prepare software that is being developed for the new missions for use in future missions.

Software assets considered as candidates for potential reuse can be registered and described in a RES where they can be found and analyzed by developers for inclusion in future systems. Refining such tools and developing additional tools to support the reuse of software can contribute to the capabilities available for both software producers and software adopters.

It is important for current missions to recognize that the systems and components they are currently developing may have the potential to be reused by future missions. Therefore, any steps they can take to make such assets more reusable will help encourage a more systematic reuse process, one that can continue to improve future missions through the realization of the benefits of software reuse.

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References


