rss_ringoccs: User Guide

Richard G. French*, Jolene W. Fong, Ryan J. Maquire, & Glenn J. Steranka
Astronomy Department, Wellesley College
Wellesley, MA 02481 USA
*Cassini Radio Science Team Leader

Contact: rfrench@wellesley.edu

August 3, 2018

Contents

List of Figures

List of Tables

1 Introduction

The Cassini Radio Science Subsystem (RSS) was used during the Cassini orbital tour of Saturn to observe a superb series of ring occultations that resulted in high-resolution, high-SNR radial profiles of Saturn's rings at three radio wavelengths: 13 cm (S band), 3.6 cm (X band), and 0.9 cm (Ka band). Radial optical depth profiles of the rings at 1- and 10-km resolution produced by the Cassini RSS team, using state of the art signal processing techniques to remove diffraction effects, are available on the NASA Planetary Data System (PDS)[1]. These archived products are likely to be quite adequate for many ring scientists, but for those who wish to generate their own diffraction-corrected ring profiles from Cassini RSS observations, we offer `rss_ringoccs`: a suite of Python-based analysis tools for radio occultations of planetary rings.[2]

The purpose of `rss_ringoccs` to enable scientists to produce "on demand" radial optical depth profiles of Saturn's rings from the raw RSS data, without requiring a deep familiarity with the complex processing steps involved in calibrating the data and correcting for the effects of diffraction. The code and algorithms are extensively documented, providing a starting point for users who wish to to test, refine, or optimize the straightforward methods we have employed. Our emphasis has been on clarity, sometimes at the expense of programming efficiency and execution time. `rss_ringoccs` does an excellent job of reproducing existing RSS processed ring occultation data already present on NASA's PDS Ring-Moons Node, but we make no claim to having achieved the state-of-the-art in every respect. We encourage users to augment our algorithms and to report on those improvements, so that they can be incorporated in future editions of `rss_ringoccs`.

This document provides an introduction to RSS ring occultations, directs users to required and recommended reading, describes in detail how to set up `rss_ringoccs`, and explains how to obtain RSS data files and auxiliary files required by the software. It provides an overview of the processing pipeline, from raw data to final high-resolution radial profiles of the rings, and guides users through a series of simple examples to illustrate the use of `rss_ringoccs`.

1.1 Getting help

We have done our best to make `rss_ringoccs` easy to install and use, but if you have questions along the way, please don't hesitate to get in touch with us. We recommend that you post an issue to the `rss_ringoccs` repository[3] so that other users can join in the conversation, but you are also free to contact the lead author of the project at the email address on the title page of this document.

1.2 What is an RSS ring occultation?

Simply put, an RSS ring occultation occurs when a radio signal transmitted from a spacecraft's High Gain Antenna (HGA) passes through the rings on the way to a Deep Space Network (DSN) receiving antenna on Earth. The received signal at Earth is affected by interactions of the radio signal with the swarm of ring particles, including attenuation, scattering, Doppler-shifting of the signal, and diffraction. We refer to the process of correcting for diffraction to obtain the intrinsic radial optical depth profile of the rings as diffraction correction or Fresnel inversion, since the correction process is based on the mathematical principles of Fresnel optics.

1.3 Overview of Cassini RSS ring observations

Over the course of the Cassini orbital tour of Saturn, the geometry of RSS ring occultations varied due both to changes in the orbiter's trajectory and to the aspect of the rings as seen from Earth during Saturn's orbit around the Sun. The opening angle of Saturn's rings as a function of time as seen from Earth is shown below in **Fig. 1**. **Jolene - would you supply figs 1, 2, and 3? Thanks!**

Figure 1: Ring Opening angle (B) vs. Time.

[1] https://pds-rings.seti.org/cassini/rss/index.html
[2] `rss_ringoccs` may be obtained from https://github.com/NASA-Planetary-Science/rss_ringoccs
[3] https://github.com/NASA-Planetary-Science/rss_ringoccs/issues

Individual occultations are identified by the Cassini rev number n, corresponding roughly to the n^{th} passage of Cassini around Saturn during which the occultation occurred. During the ingress portion of an occultation, the orbital radius of the intercept point in the ring plane of the incident ray from the spacecraft decreases with time; the radius increases with time during the egress portion of an occultation. During a diametric occultation, the ingress and egress portions of the occultation are interrupted by passage of the spacecraft behind the planet itself as seen from Earth, resulting in an atmospheric occultation. The view from Earth of the egress portion of a diametric occultation on Rev 7 is shown in **Fig. 2** below.

Figure 2: Earth view of Cassini Rev007 RSS ring occultation.

During a chord occultation, the ingress and egress occultations are contiguous. The view from Earth of the chord occultation on Rev 54 is shown in **Fig. 3** below.

Figure 3: Earth view of Cassini Rev054 RSS ring occultation.

1.4 Cassini RSS ring occultation observations on NASA's PDS

There are two categories of Cassini RSS observations on the PDS: raw data files that contain the digitized spacecraft signal as received at the DSN, and higher-level products (reduced data) that have been processed by the RSS team, such diffraction-corrected radial profiles of the optical depth of Saturn's rings and associated geometric and calibration information. `rss_ringoccs` processes raw RSR files and independently produces higher-level products that can be saved as files similar in form and content to those already on the PDS, but with a user-defined radial resolution.

1.4.1 Raw RSS data files

The raw data produced by the DSN that contain the original observations of all Cassini occultation observations are recorded in Radio Science Receiver (RSR) files, described in more detail in the *Cassini Radio Science Users Guide* (Section 1.5.1). During Cassini RSS occultations, RSR files were typically recorded at two bandwidths: 1 kHz and 16 kHz. The `rss_ringoccs` package can handle either version, and they give nearly identical results, although the processing time for the 16 kHz files is slightly longer.

At the present time, only the 16 kHz files are available on the PDS, although there are plans to archive the 1 kHz files if funding and human resources are available (likely during 2019). We provide convenient scripts in `rss_ringoccs` (Section 2.5) to download RSR files from the PDS archive.

1.4.2 Higher-level products

Essam Marouf of the Cassini RSS team has produced two sets of higher-level products for ring occultation observations. The first can be found at `https://pds-rings.seti.org/cassini/rss/index.html`. This archive set contains 1- and 10-km resolution diffraction-corrected profiles from X-band observations of Revs 7 through 67. Navigate to the dataset `CORS_8001` and then to the `EASYDATA` subdirectory. Within this directory, occultation data sets are organized by name: `RevXXev_RSS_yyyy_doy_Xd/` (for example, `Rev07E_RSS_2005_123_X43_E/`) where

- `XX` is the rev number (ex: 07)
- `ev` is the event type (ex: E)
    - `I` for ingress
    - `E` for egress
    - `CI` for ingress portion of chord occultation
    - `CE` for egress portion of chord occultation
- `yyyy` is the UTC year of the start of the occultation (ex: 2005)
- `day` is the UTC day of year of the start of the occultation (ex: 123)

- `X` indicates that the observations were made at X-band
- `d` is the direction (`I` for ingress, `E` for egress) (ex: E)

Each occultation data set directory contains a set of `*.LBL` label files that describe counterpart `*.TAB` ASCII data tables or a summary PDF file. For example:

- `Rev07E_RSS_2005_123_X43_E_Summary.pdf` contains an overview of the occultation
- `RSS_2005_123_X43_E_CAL.TAB` contains calibration information
- `RSS_2005_123_X43_E_GEO.TAB` contains geometry information
- `RSS_2005_123_X43_E_TAU_01KM.TAB` contains the diffraction-corrected optical depth profile of the rings at 1 km resolution
- `RSS_2005_123_X43_E_TAU_10KM.TAB` contains the diffraction-corrected optical depth profile of the rings at 10 km resolution

A second (and more extensive) set of higher-level products produced by RSS team member Essam Marouf is currently under peer review by the PDS. It contains diffraction-corrected optical depth profiles at 1- and 10-km resolution for all S, X, and Ka-band ring occultation observations from Revs 7 through 137, and in addition to the file types enumerated above, includes intermediate `DLP` files that contain the normalized *diffraction-limited* observations that are the input for the diffraction reconstruction stage of the analysis.[4] Once this second delivery of higher-level products has been officially accepted by the PDS in its final form, this document will be updated to provide additional details about these higher-level products.

`rss_ringoccs` has the ability to produce `CAL, GEO, DLP`, and `TAU` files that users can compare directly with the two sets of higher-order products just described.

1.5 Required and recommended reading

With this overview of RSS ring occultation observations and data in hand, we strongly recommend that all users next familiarize themselves with several key documents before embarking on serious use of the `rss_ringoccs` package. Our internal documentation of the `rss_ringoccs` code makes frequent reference to the following two documents:

1.5.1 Cassini Radio Science User's Guide

The most complete practical introduction to Cassini RSS ring observations is contained in the *Cassini Radio Science User's Guide*.[5] We regard this as *required reading*. Chapter 2 describes the *open loop* RSR files that contain the raw RSS ring occultation data, and Chapter 3.3 summarizes the analysis steps in obtaining a diffraction-corrected ring optical depth profile from the observations. *For the remainder of this guide, we will assume that all readers have familiarized themselves with this material.*

1.5.2 Marouf, Tyler, and Rosen (1986) - MTR86

The definitive reference for diffraction correction of RSS occultations is Marouf et al. (1986): Marouf, Tyler and Rosen's classic "Profiling Saturn's rings by radio occultation" – we refer to this as MTR86. For copyright reasons, we cannot include MTR86 in this GitHub repository, but every serious student of radio occultations should have this paper readily at hand. It documents the Fresnel inversion method of diffraction correction, with application to Voyager RSS occultation observations of Saturn's rings. This is *recommended reading* for beginning users of `rss_ringoccs`, and *required reading* for anyone wishing to understand the inner workings of the `rss_ringoccs` software package.

[4] We have used these results to provide independent tests of the ability of `rss_ringoccs` to process the raw data up to the point of diffraction-limited profiles, and to perform the diffraction correction to produce final optical depth profiles.

[5] Available from `https://pds-rings.seti.org/cassini/rss/`

1.5.3 For more information...

Readers interested in an overview of Cassini RSS instrumentation and science goals are encouraged to read Kliore et al.'s "Cassini Radio Science" Kliore et al. 2004. Scientific results making use of Cassini RSS occultation observations include Colwell et al. 2009; Moutamid et al. 2016; French et al. 2016a,b, 2017 and Marouf et al. 2011; Nicholson et al. 2014a,b; Rappaport et al. 2009; Thomson et al. 2007.

2 Setting Things Up

This section provides step-by-step instructions on setting up the `rss_ringoccs` package and associated data files. Experienced users may wish instead to refer to the document *Quick-Start Installation Guide for rss_ringoccs*.[6] We assume that all users are familiar with basic unix commands (FILL OUT IN MORE DETAIL LATER) and have an introductory-level command of Python.

2.1 System requirements

The `rss_ringoccs` repository has been developed and tested on the following hardware, unix-based operating systems, and shells:

Hardware	Operating System	Shell	GB of RAM
MacBookPro, iMac	MacOS High Sierra 10.13.4	csh, bash	8, 16, and 32
MacBookPro	Linux Ubuntu Budgie 16	bash	8
MacBookPro	Linux Ubuntu 16	bash	8
MacBookPro	Linux Debian	bash	8
MacBookPro	Linux Fedora	bash	8

Table 1: Hardware and Operating Systems

2.2 Install Python 3 and required packages

`rss_ringoccs` has been tested under both Python 2.7 and Python 3, but we strongly recommend that users install Python 3, since Python 2.7 will not be supported after 2020.[7] Our code has been tested under the following Python configurations: **Ryan - update this table**

Operating System	Python Distribution	Version	URL
MacOS 10.13.4	Enthought Canopy	Python 3.5.2	https://www.enthought.com
MacOS 10.13.4	Anaconda	Python 3.6.3	https://www.anaconda.com
Linux Ubuntu Budgie 16	xxxx	xxxx	https://www.ubuntu.com
Linux Ubuntu 16	xxxx	xxxx	https://www.ubuntu.com
Linux Debian	xxxx	xxxx	https://www.debian.org
Linux Fedora	xxxx	xxxx	https://getfedora.org

Table 2: Python Versions

Install the following Python packages required by `rss_ringoccs`, illustrated here using `pip`.[8] Enter the following commands in a terminal at the unix command line:

```
host:~ user$ pip install matplotlib
host:~ user$ pip install numpy
host:~ user$ pip install pytest
host:~ user$ pip install six
host:~ user$ pip install Scipy
```

[6] Located in `rss_ringoccs/docs/`.
[7] https://pythonclock.org/
[8] https://pip.pypa.io/en/stable/

2.2.1 Download and install spiceypy

rss_ringoccs makes extensive use of JPL's NAIF SPICE toolkit Acton (1996), a set of software tools to calculate planetary and spacecraft positions, ring occultation geometry, and a host of useful calendar functions.[9] Our software requires spiceypy, a Python-based interface to the NAIF toolkit, available from https://github.com/AndrewAnnex/SpiceyPy. Follow the installation instructions on this website, or use pip:

```
host:~ user$ pip install spiceypy
```

2.2.2 Test spiceypy

To test your installation of spiceypy, fire up Python in a terminal at the unix command line and at the >>> prompts, enter the following commands, and confirm that spiceypy returns π and the speed of light c:

```
host:~ user$ python
>>> from __future__ import print_function
>>> import spiceypy
>>> print(spiceypy.pi(),spiceypy.clight())
3.141592653589793 299792.458
>>> exit()
```

2.3 Download and install the rss_ringoccs repository from GitHub

Follow these steps to download and install rss_ringoccs:

- Visit https://github.com/NASA-Planetary-Science/rss_ringoccs and click the green *Clone or Download* pull-down menu at the upper right.
- Download the zip file rss_ringoccs-master.zip to your local Downloads directory. For this example, this is ~/Downlaods.
- Identify the destination directory under which you wish to install rss_ringoccs. For this example, the destination directory is ~/local. (This should be on a large-capacity disk drive or partition (1 TB or larger), since raw Cassini RSS data files are quite large. We recommend that this be routinely backed up.)
- Use your favorite utility to unzip the file. This will create the rss_ringoccs-master directory and several sub-directories. For example:

```
host:~ user$ cd ~/local
host:~ user$ unzip ~/Downloads/rss_ringoccs-master.zip
host:~ user$ ls -1F rss*
rss_ringoccs-master:
AAREADME.txt
LICENSE
README.md
certification/
data/
docs/
examples/
figs/
input/
kernels/
output/
src/
```

- We suggest that you read the top-level AAREADME.txt to familiarize yourself with the organization of the rss_ringoccs package and installation instructions.

[9] See https://naif.jpl.nasa.gov/naif/index.html

2.4 Download the required JPL/NAIF SPICE kernels

The rss_ringoccs package makes extensive use of SPICE data (*kernel* files) from JPL/NAIF that specify planetary and spacecraft ephemerides, planetary constants, and other essential information for computing the geometric circumstances of occultations.[10] rss_ringoccs contains bash-based shell scripts to automate the retrieval of SPICE kernels from the NAIF website and store them in subdirectories under rss_ringoccs/kernels/, following the same directory structure as on the NAIF ftp site. Some of the kernel files are quite large, and will take some time (and significant disk space) to download. For quick setup and testing purposes, a minimal set of essential kernels is required. To download these, navigate to the directory containing the rss_ringoccs-master directory, and enter the following commands at the command line of a terminal window:

```
host:~ user$ cd rss_ringoccs-master/src
host:~ user$ ./get_kernels.sh ../input/essential_kernels.txt ../kernels
host:~ user$ cd ../kernels
host:~ user$ ls -lR
```

You should have a listing the resembles the following:

```
host:~ user$ cd ../kernels
Show results of ls -lR
```

You will notice that there are several Cassini-specific kernel files. Among them are the so-called *reconstructed trajectory* files. For example, 050606R_SCPSE_05114_05132.bsp is a reconstructed Cassini trajectory file produced on 2005 June 6 (050506) that spans the period 2005 day of year 114 to 132 (05114 to 05132), or April 24 to May 12, 2005.

In order to compute the geometry of RSS occultations throughout the Cassini orbital tour, a larger set of these large trajectory files is required. Once you have completed the initial tests of rss_ringoccs, we recommend that you download this more complete set of files, using the commands below:

```
host:~ user$ cd rss_ringoccs-master/src
host:~ user$ ./get_kernels.sh ../input/all_kernels.txt ../kernels
host:~ user$ cd ../kernels
host:~ user$ ls -lR
```

The shell script detects whether a given kernel has already been downloaded, so you may interrupt this command if it hasn't run to completion in the time you have available, and repeat the command later, picking up the downloading process where it left off the previous time. Once you have downloaded the complete set of kernels, you will not need to repeat this process unless JPL releases an updated set of Cassini trajectory files. We plan to update this documentation and the input files for get_kernels.sh if that occurs.

2.5 Download essential Cassini RSS raw data files

The rss_ringoccs package requires local access to raw Cassini RSS data files (Section 1.4.1). The storage capacity on GitHub is not sufficient to allow even one sample RSR file to be part of the standard download. Instead, as with the kernels files described above, we provide a script to download a minimal set of RSR files for the initial tests of rss_ringoccs:

```
host:~ user$ cd rss_ringoccs-master/src
host:~ user$ ./get_rsr_files.sh ../input/essential_rsr-files.txt ../data
host:~ user$ cd ../data
host:~ user$ ls -lR
```

You should have a listing the resembles the following:

```
host:~ user$ cd ../data
host:~ user$ ls -lR
Show results of ls -lR
```

[10] For detailed information about kernels, visit https://naif.jpl.nasa.gov/naif/data.html.

The deeply-nested directory structure of the downloaded data follows that of the PDS website from which the RSR files are retrieved, so that users can easily determine the original source of each RSR file. (Note that only a subset of the RSS files on the PDS is downloaded; the complete PDS distribution contains many additional files that are not needed by `rss_ringoccs`.) The `cors_xxxx` prefix refers to the Cassini Orbiter Radio Science PDS delivery `xxxx`. Underneath these directories are directories with names such as `sroc1_123`, which somewhat cryptically refers to a Saturn ring occultation (`sroc`) on day of year 123 of the year during which the data were taken. The RSR files of interest are located in next level `rsr` subdirectories. A typical name is `s10sroe2005123_0740nnnx43rd.2a2`. Decoded, this occultation was part of Cassini sequence 10, it was part of a Saturn ring occultation (`sro`) – egress (`e`) – in year 2005, day of year 123, beginning at UTC 07:40, recorded at X band (`x`) from Deep Space Network (DSN) station DSS-43. The `r` in `rd.2a2` refers to *right hand circular polarization*, appropriate for all RSS ring occultation observations used by `rss_ringoccs`.

2.6 Install Jupyter Notebook (optional but recommended)

All of our tutorials make use of Jupyter Notebook, a widely-used open-source web application that allows users to create and share documents that contain live code, equations, visualizations and narrative text.[11] While not required for `rss_ringoccs`, we strongly recommend that you install and familiarize themselves with Jupyter Notebook so that you can make use of the tutorials we have supplied. Jupyter Notebook comes pre-installed with the Anaconda distribution of Python. For other versions of Python, you can use Python's package manager, `pip`. If you have Python 3 installed (which is recommended):

```
host:~ user$ python3 -m pip install --upgrade pip
host:~ user$ python3 -m pip install jupyter
```

If you have Python 2 installed:

```
host:~ user$ python -m pip install --upgrade pip
host:~ user$ python -m pip install jupyter
```

Jupyter Notebook is run in a web browser. For `rss_ringoccs`, you would typically navigate in a terminal window to a directory containing an existing notebook (notebooks have the suffix `.ipynb`, such as `tutorial_example.ipynb` in the example below), and then start the application using the following commands in a terminal window:

```
host:~ user$ cd rss_ringoccs-master/tutorials
host:~ user$ jupyter notebook tutorial_example.ipynb
```

We recommend that you try this example now. It confirms that you have successfully navigated your way to the `tutorials` directory, lists the tutorial notebooks and the PDF files that contain the sample output of running each tutorial, and a simple plot.

For more information about installing and using Jupyter Notebook, visit http://jupyter.org/install.

3 Getting Started with rss_ringoccs

Now that you have installed `rss_ringoccs` and downloaded the essential kernels and RSR files, you are ready to run some simple initial tests of `rss_ringoccs` to confirm that everything is working properly, and to familiarize yourself with the software. First, though, a few conventions and requirements:

- No reference is made within the `rss_ringoccs` package to local directories outside of the top-level `rss_ringoccs-master/` hierarchy of directories.
- The directory structure under `rss_ringoccs-master/` *must* strictly follow that of the original download from the GitHub repository.
- For portability, all references within `rss_ringoccs` software to pathnames to other directories within `rss_ringoccs-master/` are relative, not absolute.
- Unless otherwise noted (as in the tutorials, for example), all executable scripts and Python programs *must* be run from within the `rss_ringoccs-master/src/` directory. (This is so that relative pathnames will point to the correct directories.)

[11]For more information, visit http://jupyter.org/

3.1 A tutorial on tutorials - using a Jupyter notebook

Show how to read an existing Jupyter notebook or just the pdf.

3.2 Initial test of `rss_ringoccs`

The first test of `rss_ringoccs` is to produce a 1-km resolution diffraction-corrected profile of the Saturn's Huygens ringlet from the `Rev007` egress occultation, observed at X band from DSS-43. (This is an example included in Section 3.3 of the *Cassini Radio Science User's Guide*.) To speed up the process, we will make use of some pre-computed results, already present on the GitHub repository; below, we will show how these pre-computed results were obtained.

```
host:~ user$ cd rss_ringoccs-master/src
host:~ user$ python rss_ringoccs_Rev007EX43_HuygensRinglet_test.py
```

This run should produce a plot of the diffraction pattern and phase, optical depth, power, and phase. It should be a sequence of calls

3.3 Additional tests of `rss_ringoccs`

4 Overview of the Processing Pipeline

Ryan's nice pipeline figure goes here. Say that our processing steps are designed to produce files that are the same type as what is on the PDS archive. Explain that using files is not required and that we have separate small routines to read and write the standard format files.

4.1 Computing the geometry of an occultation – producing a GEO file

Point to the required jupyter notebooks for the main command, and the separate one with a tutorial that goes through each step

4.2 Obtaining the diffraction-limited profile of an occultation

4.2.1 Frequency correction

Point to the Jupyter notebook for the main command, and the separate one with a tutorial that goes through each step.

4.2.2 Power normalization

Point to the Jupyter notebook for the main command, and the separate one with a tutorial that goes through each step.

4.2.3 Producing a CAL file

Point to the Jupyter notebook for the main command, and the separate one with a tutorial that goes through each step.

4.2.4 Producing a DLP file

Point to the Jupyter notebook for the main command, and the separate one with a tutorial that goes through each step.

4.3 Retrieving the ring optical depth profile from the diffraction pattern

4.3.1 Preparing for the diffraction correction

Two options - get the output from the previous code steps as a class instance, or read the necessary files. Need to specify desired radial range and resolution and window type.

4.3.2 Computing the diffraction-corrected profile

Point to the Jupyter notebook for the main command, and the separate one with a tutorial that goes through each step.

4.3.3 Producing a TAU file

Show simple Jupyter notebook that does this

5 More Detailed Examples

5.1 Full end-to-end example

Point to jupyter notebook that runs this command, with comments.

5.2 Zooming in on a particular ring feature for a specified resolution

Show example of Maxwell ringlet at 0.5, 2.0 resolution.

6 Looking under the hood: the `rss_ringoccs` software package

Add a table of all of the functions / methods / classes.

6.1 Occultation geometry routines

6.2 Diffraction pattern routines

6.3 Diffraction correction routines

6.4 Utility routines

7 Where To Go From Here

7.1 The Cassini RSS data catalog

7.2 Selecting an RSR file to process

Depends on elevation angle, antenna size and snr, radius range covered, ring opening angle.

7.3 Practical considerations

execution time, SNR, radial resolution, sampling theorem

7.3.1 Benchmarks

Rev	RSR file	Band	Radial Range	ΔR_{res} (km)	GEO	CAL	DLP	TAU	Total (sec)

Table 3: Benchmarks

7.3.2 Potential speed improvements

FFTW
Cython
Algorithms
Multiprocessing

7.4 Assumptions and limitations

Comment on assumptions of MTR86

7.5 The Complete User's Guide

For those who wish to understand the theory behind the diffraction-correction methods in `rss_ringoccs`, we direct you to the much more comprehensive document.

8 Certification: Confirming that `rss_ringoccs` works

We've left until the end some important evidence that the diffraction correction methods we've used actually work!
Calculating power for the first few points of rev7E X43:

SPM	I + i*Q	Power ($I^2 + Q^2$)
27600.000	-485 + i* -948	1133929
27600.001	-348 + i* -1602	2687507
27600.002	200 + i* 1252	1607503
27600.003	-122 + i* 491	255965
27600.004	-784 + i* -1436	2676751
27600.005	298 + i* 1436	2150900
27600.006	262 + i* 61	72364
27600.007	907 + i* -60	826249
27600.008	550 + i* 666	746056
27600.009	327 + i* 732	642753
27600.010	581 + i* -749	898562
27600.011	-221 + i* -1026	1101516
27600.012	1836 + i* 282	3450419
27600.013	435 + i* -213	234594
27600.014	101 + i* -694	491836
27600.015	-394 + i* 512	417379
27600.016	-1428 + i* -241	2097265
27600.017	49 + i* 749	563402
27600.018	65 + i* 336	117120
27600.019	199 + i* -1197	1472409

Verifying that $I^2 + Q^2$ gives about the same power as in figure 4 in free-space regions (4×10^9):

SPM	I + i*Q	Power ($I^2 + Q^2$)
30098.500	16702 + i*-10071	380381845
30098.501	15572 + i*-13571	426659224
30098.502	13159 + i*-14707	389455130
30098.503	9620 + i*-17455	397221425
30098.504	4047 + i*-18619	363045370
30098.505	41 + i*-19685	387500906
30098.506	-2256 + i*-20521	426200977
30098.507	-7462 + i*-17844	374089780
30098.508	-11279 + i*-16215	390142066
30098.509	-13825 + i*-14011	387438745
30098.510	-16566 + i*-11774	413059432
30098.511	-17755 + i* -8652	390097129
30098.512	-17923 + i* -4588	342283673
30098.513	-19072 + i* -1110	364973284
30098.514	-21170 + i* 4117	465118588
30098.515	-18766 + i* 7755	412302781
30098.516	-17140 + i* 10456	403107536
30098.517	-14604 + i* 13141	385962696
30098.518	-9846 + i* 15803	346678524
30098.519	-7257 + i* 19298	425076852

8.1 Comparison with independent results on PDS

Important - our results are completely independent implementation of MTR86 - no software in common at all. Confirms both implementations.

8.1.1 Rev007E

Diametric occultation - show geometry plot from Earth. Show S, X, Ka band of Maxwell Ringlet at 1 km.

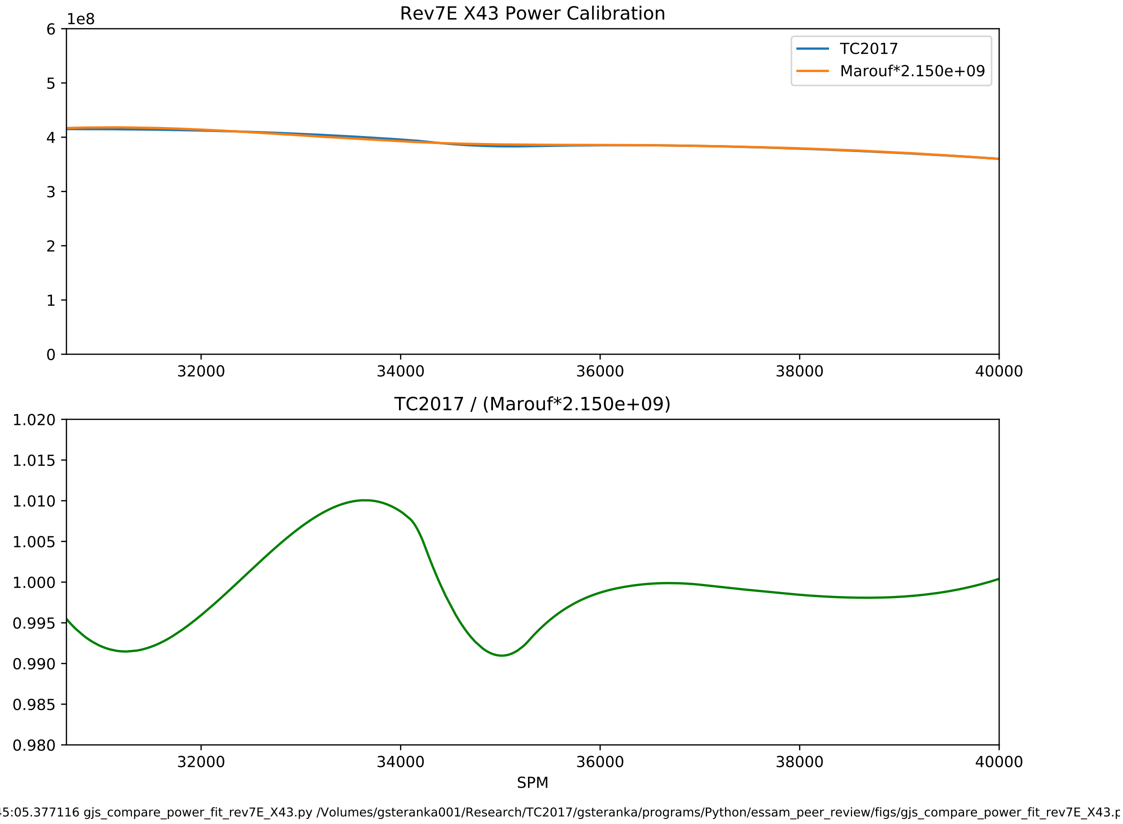


Figure 4: Comparison of power normalization curves from CAL files for rev7E X43. Verifies that there is a constant factor difference of 2.15×10^9

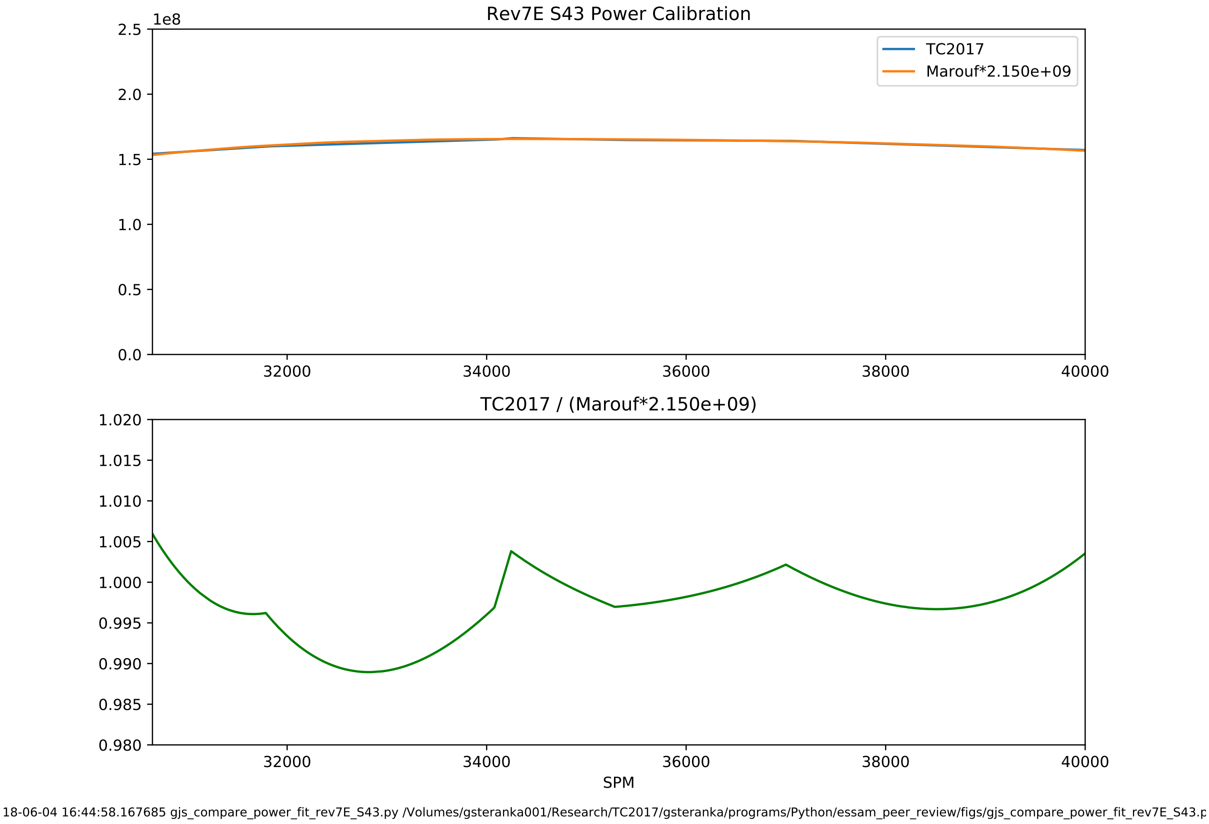


Figure 5: Comparison of power normalization curves from CAL files for rev7E S43. Verifies that there is a constant factor difference of 2.15×10^9

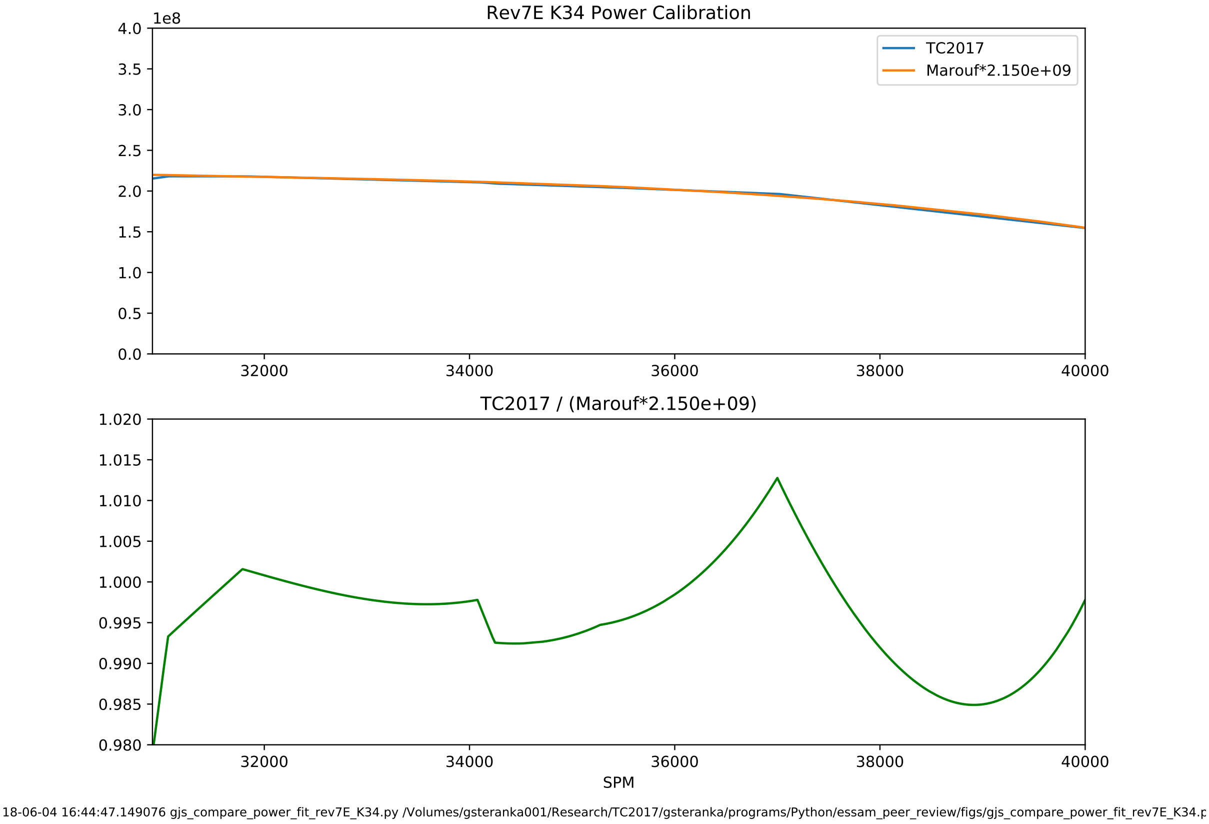
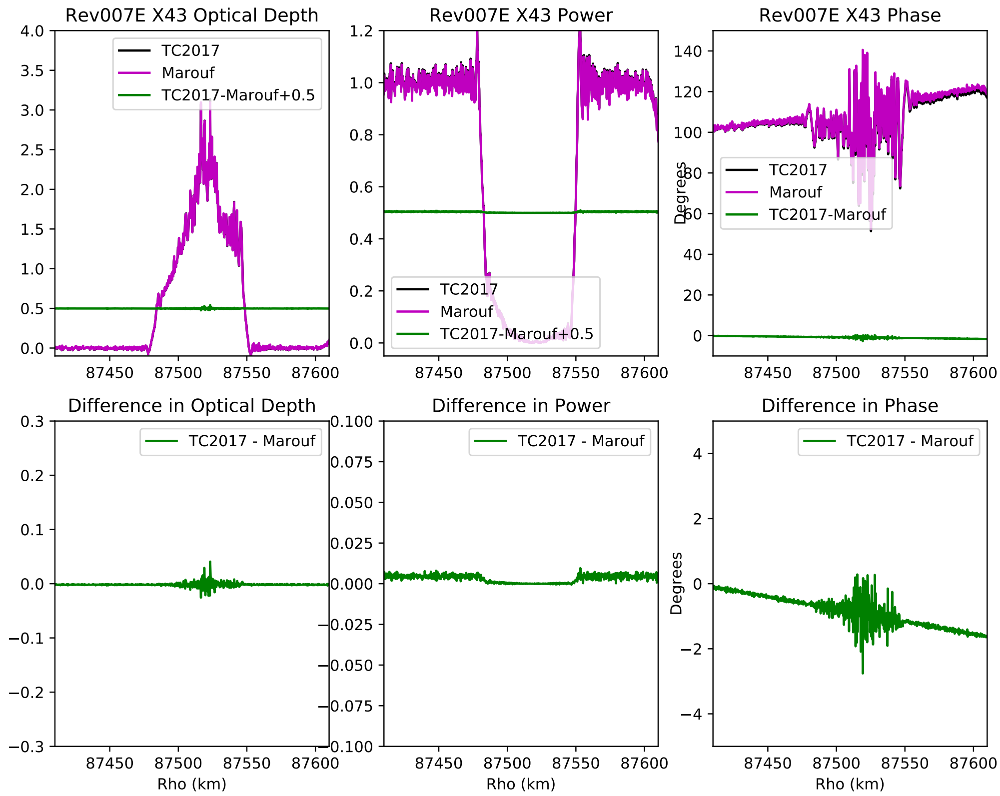
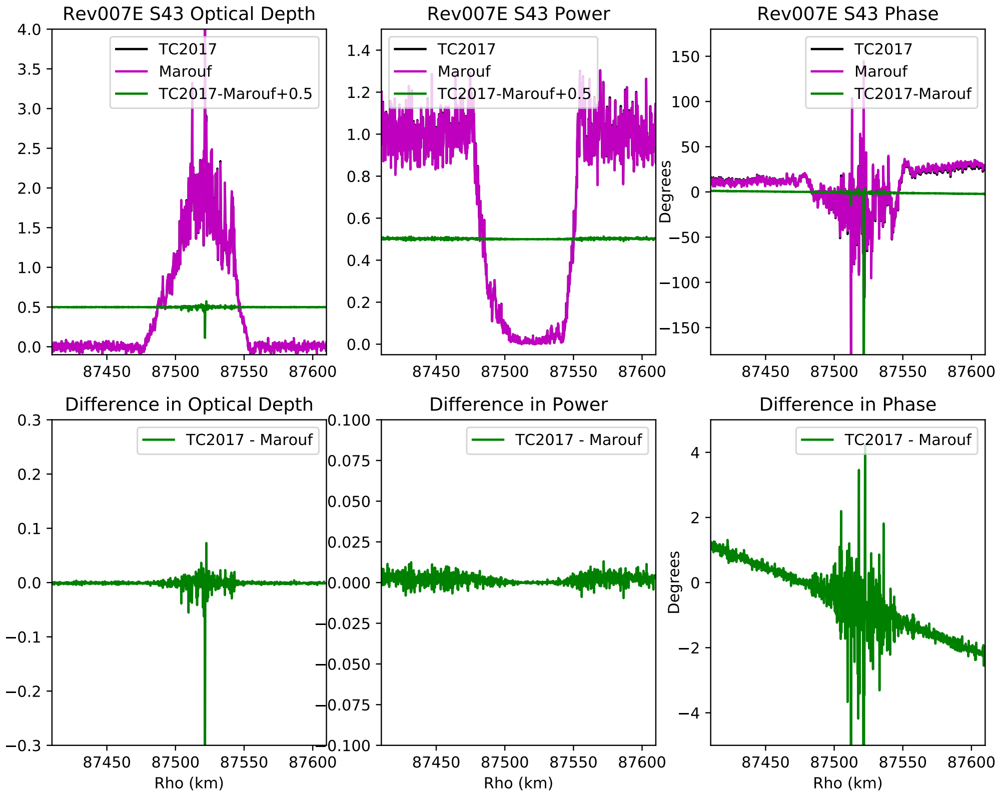


Figure 6: Comparison of power normalization curves from CAL files for rev7E K34. Verifies that there is a constant factor difference of 2.15×10^9



2018-05-31 11:50:40.052104 gjs_compare_dlp_v2_rev7E_X43.py /Volumes/gsteranka001/Research/TC2017/gsteranka/programs/Python/essam_peer_review/figs/gjs_compare_dlp_v2_rev7E_X43.pdf

Figure 7: Comparison of rev7E X43 optical depth and phase profiles before inversion



2018-05-31 15:34:45.608879 gjs_compare_dlp_v2_rev7E_S43.py /Volumes/gsteranka001/Research/TC2017/gsteranka/programs/Python/essam_peer_review/figs/gjs_compare_dlp_v2_rev7E_S43.pdf

Figure 8: Comparison of rev7E S43 optical depth and phase profiles before inversion

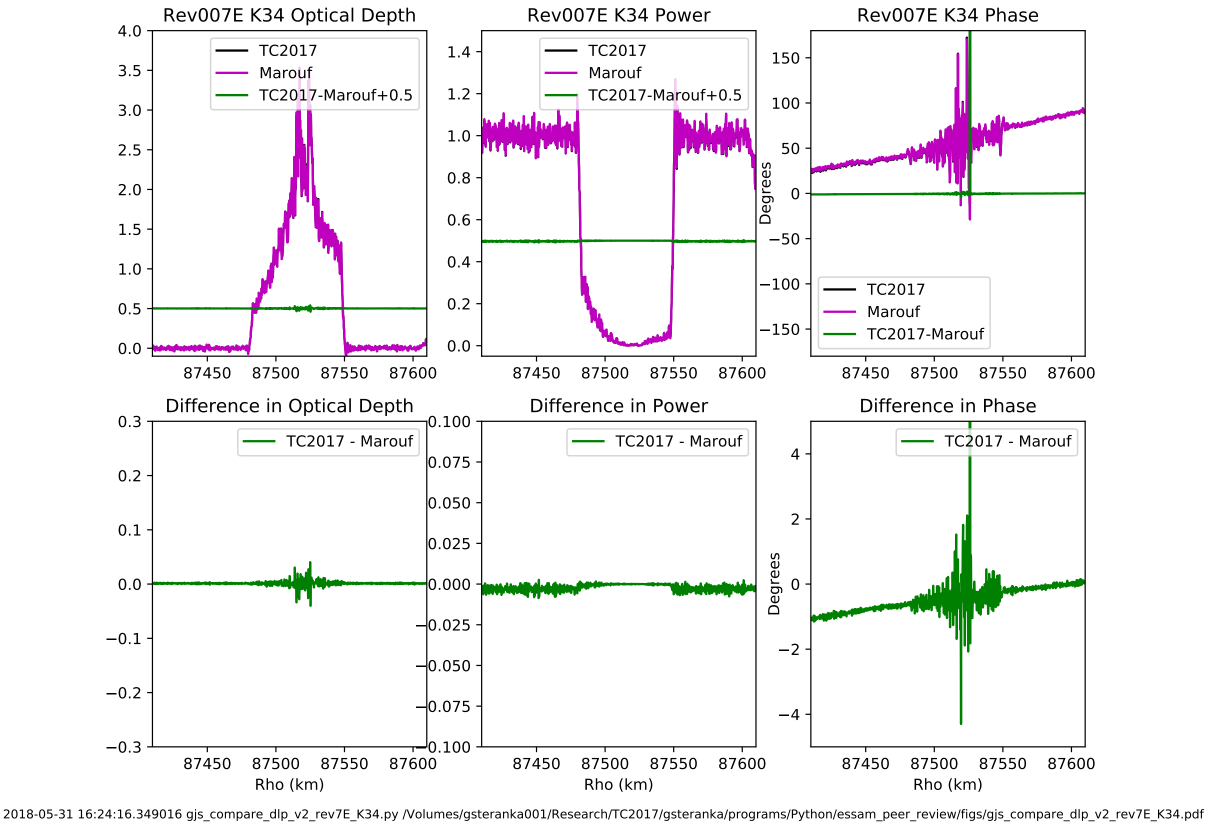


Figure 9: Comparison of rev7E K34 optical depth and phase profiles before inversion

8.1.2 Rev054

This is a chord occultation and requires special attention. Show geometry plot from Essam. Show S, X, Ka band of Maxwell Ringlet I and E if present, otherwise a density wave.

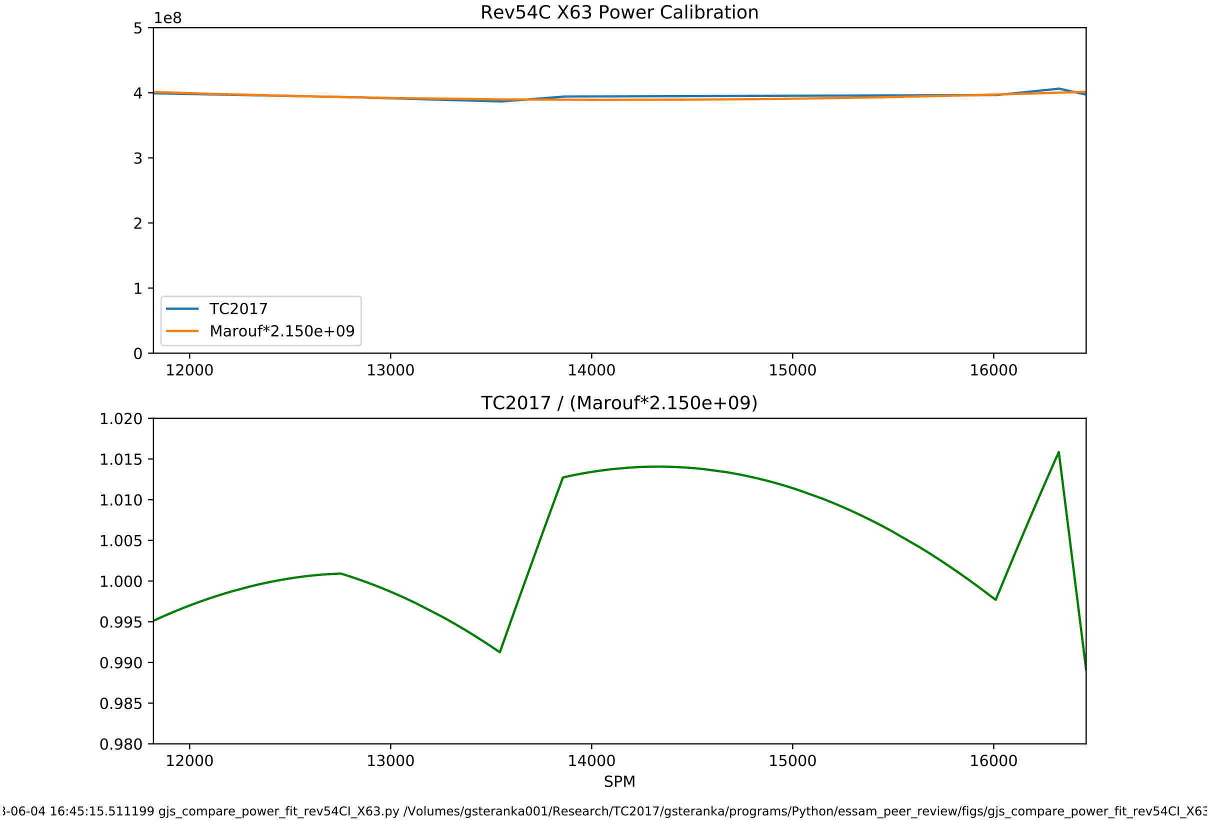


Figure 10: Comparison of power normalization curves from CAL files for rev54C X63. Verifies that there is a constant factor difference of 2.15×10^9

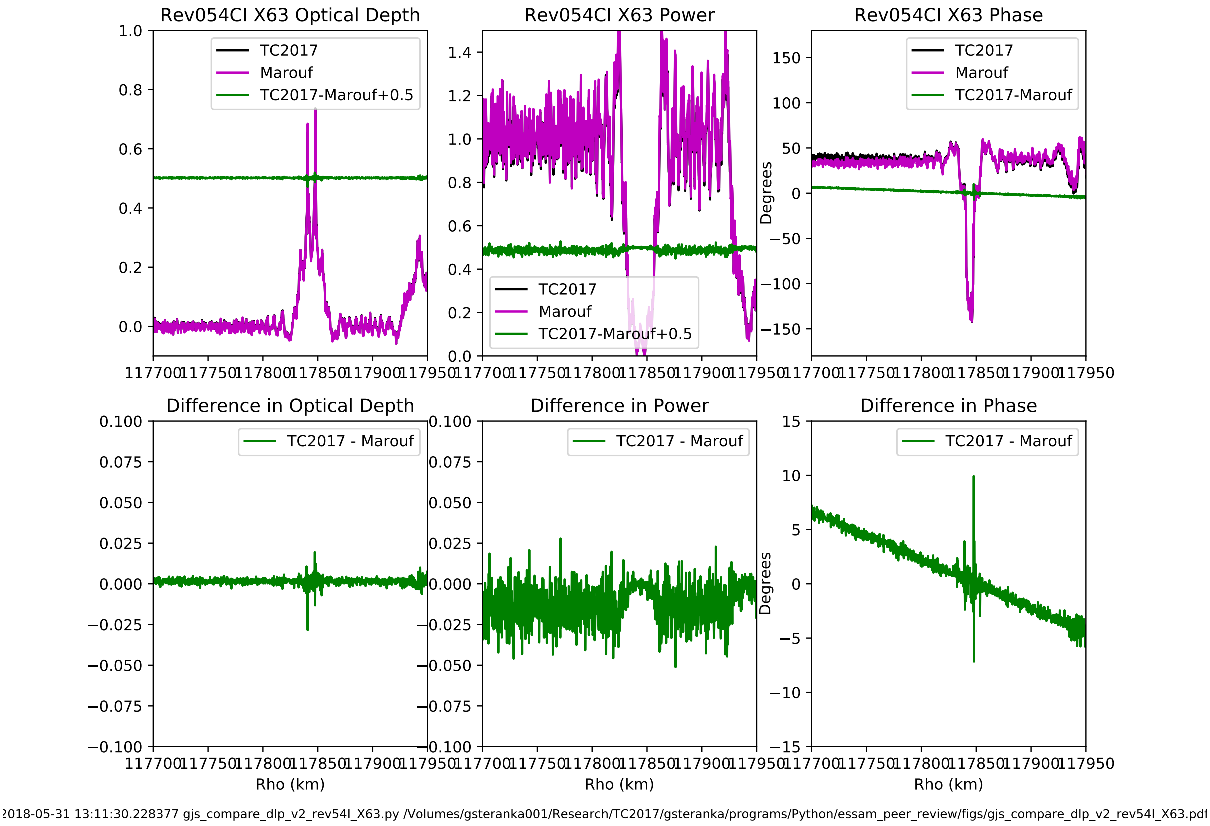


Figure 11: Comparison of rev54CI X63 optical depth and phase profiles before inversion

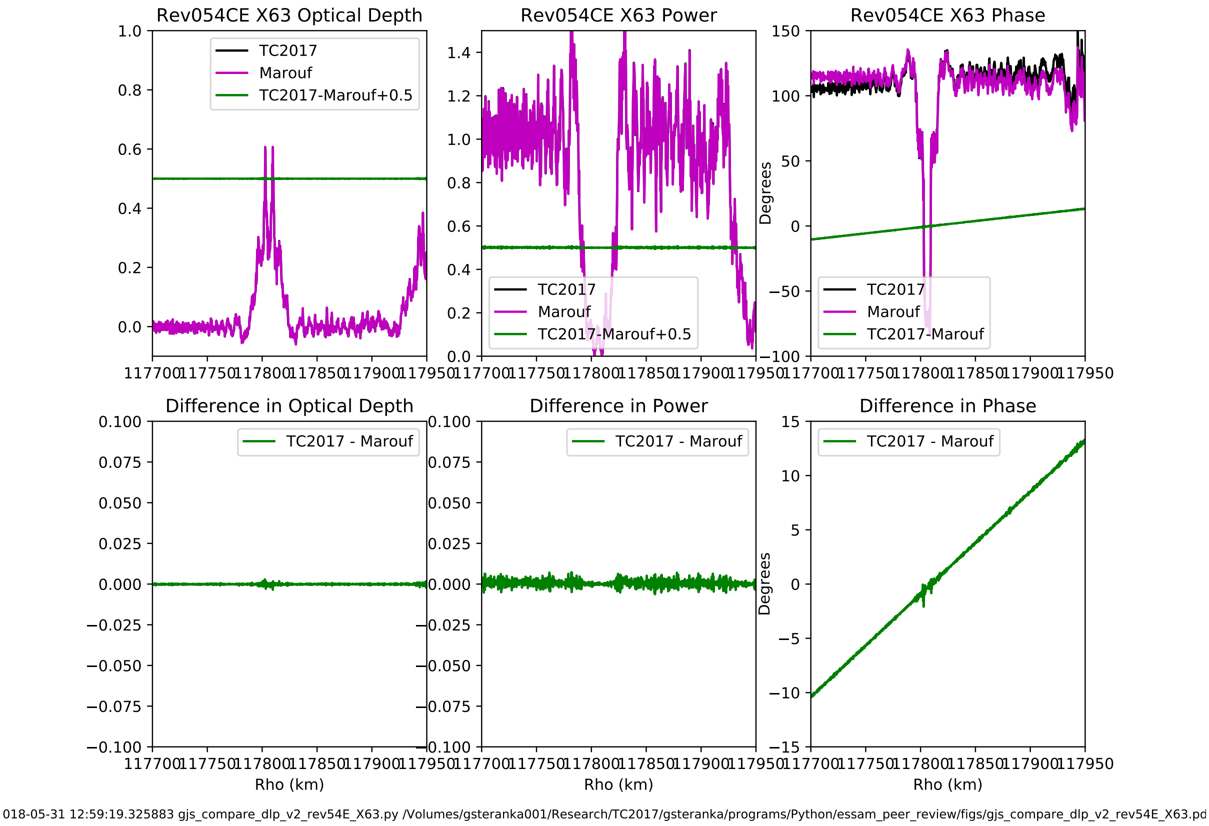


Figure 12: Comparison of rev54CE X63 optical depth and phase profiles before inversion

8.2 Some idealized examples

8.2.1 A simple isolated sharp-edged ringlet

8.2.2 A more complex ringlet - forward and inverse calculations

8.3 Comparison with *Voyager* results

8.3.1 Reproducing MTR86 results for Voyager 2 at Saturn

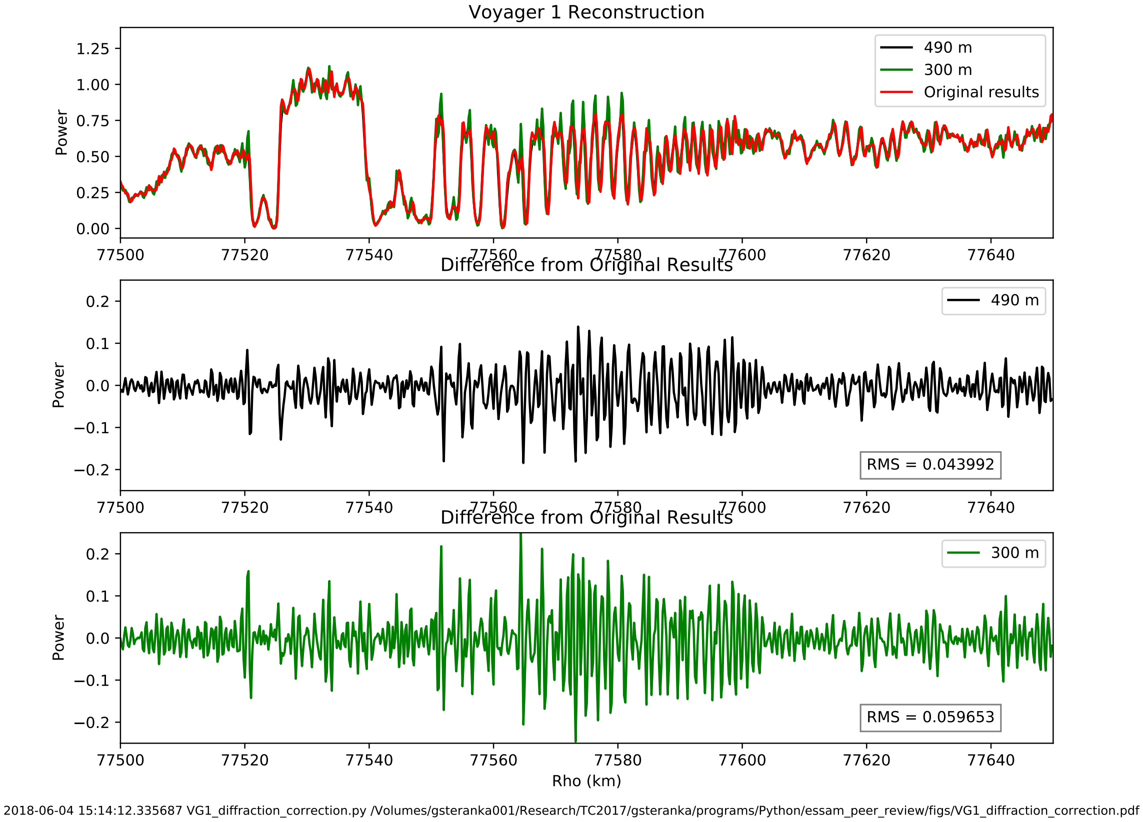


Figure 13: MTR86 figure 19 comparison, in power instead of optical depth

8.3.2 Reproducing Gresh results for Voyager 2 at Uranus?

9 Acknowledgements

Development of `rss_ringoccs` was supported by NASA/JPL as part of the Cassini Mission Closeout effort. The authors especially appreciate the support and encouragement of Linda Spilker and Kathryn Weld. We dedicate this work to the memory of Arv Kliore, the original Cassini RSS Team Leader and an example of wisdom and kindness for us all.

Acronyms

AU Astronomical Unit. *Glossary:* Astronomical Unit
BSR Bistatic Radar. *Glossary:* Bistatic Radar
CFT Continuous Fourier Transform. *Glossary:* Continuous Fourier Transform
DC Direct Current. *Glossary:* Direct Current
DSN Deep Space Network. 1, *Glossary:* Deep Space Network
ERT Earth Received Time. *Glossary:* Earth Received Time
ESA European Space Agency. *Glossary:* European Space Agency
ET Ephemeris Time. *Glossary:* Ephemeris Time
FFT Fast Fourier Transform. *Glossary:* Fast Fourier Transform
FIR Finite Impulse Response. *Glossary:* Finite Impulse Response
FOIL First Outside Inner Last. *Glossary:* FOIL
GHz GigaHertz. *Glossary:* GigaHertz
GPS Global Positioning System. *Glossary:* Global Positioning System
GR General Relativity. *Glossary:* General Relativity
GW Gravitation Wave. *Glossary:* Gravitational Wave
GWE Gravitation Wave Experiment. *Glossary:* Gravitational Wave Experiment
HGA High Gain Antenna. 1, *Glossary:* High Gain Antenna
Hz Hertz. *Glossary:* Hertz
IF Intermediate Frequency. *Glossary:* Intermediate Frequency
JPL Megabyte. *Glossary:* Jet Propulsion Laboratory
KAT K_a-band Translator. *Glossary:* K_a-band transponder
KHz KiloHertz. *Glossary:* KiloHertz
LCP Left-hand Circularly Polarized. *Glossary:*
MB Megabyte. *Glossary:* Megabyte
MHz MegaHertz. *Glossary:* MegaHertz
NAIF Navigation Ancillary Information Facility. *Glossary:* NAIF
NASA National Aeronautic and Space Administration. 1, *Glossary:* NASA
OD Orbit Determination. *Glossary:* Orbit Determination
Opmode Operations Mode. *Glossary:* Operations Mode
PDS Planetary Data System. 1, *Glossary:* Planetary Data System
PEMDAS Parenthesis Exponents Multiplication Division Addition Subtraction. *Glossary:* PEMDAS
PLL Phase-Lock Loop. *Glossary:* Phase-Lock Loop
PSA Planetary Science Archive. *Glossary:* Planetary Science Archive
RCP Right-Hand Circularly Polarized. *Glossary:* Right-Hand Circulary Polarized
Rev Revolution. *Glossary:* Rev
RF Radio Frequency. *Glossary:* Right-Hand Circulary Polarized
RMS Root Mean Square. *Glossary:* Root Mean Square
RS rs. *Glossary:* Radio Science
RSR Radio Science Receiver. 2, 3, *Glossary:* Radio Science Receiver
RSS Radio Science Subsystem. 1, *Glossary:* Radio Science Subsystem
RTG Radioisotope Thermonuclear Generator. *Glossary:* Radioisotope Thermonuclear Generator
SCE Solar Conjunction Experiment. *Glossary:* Solar Conjunction Experiment
SNR Signal-to-Noise Ratio. *Glossary:* Signal-to-Noise Ratio
SPICE Spacecraft, Planet, Instrument, C-Matrix, Events. *Glossary:* SPICE
TDB Barycentric Dynamical Time. *Glossary:* Barycentric Dynamical Time
TLM Telemetry. *Glossary:* Telemetry
USO Ultra-Stable Oscillator. *Glossary:* Ultra-Stable Oscillator
UTC Universal Time Coordinated. *Glossary:* Universal Time Coordinated

Glossary

Atmospheric occultation	Disappearance or reappearance of a source after the signal has passed through the atmosphere of a planet or satellite. 2
Chord occultation	Ring occultation. 2
Deep Space Network	NASA's complex of Earth-based antennas, used to communicate with spacecraft. 1
Diametric occultation	An occultation geometry in which the path of the complete occultation extends from ring ansa to ring ansa, passing behind the planet at mid-occultation.. 2
Diffraction correction	Retrieval of intrinsic optical depth profile of the rings by removing the effects of diffraction in the observed signal. 1
Egress	Exit phase of a ring or atmosphere occultation. 2
Fresnel inversion	Retrieval of intrinsic optical depth profile of the rings by using a Fresnel transform to correct for the effects of diffraction in the observed signal. 1
GigaHertz	10^9 Hertz. *see* Hertz
High Gain Antenna	Highly directional main spacecraft antenna for communications and radio science. 1
Ingress	Entry phase of a ring or atmosphere occultation. 2
KiloHertz	10^3 Hertz. *see* Hertz
Megabyte	10^6 bytes. *see* byte
MegaHertz	10^6 Hertz. *see* Hertz
NASA	National Aeronautics and Space Administration. 1
Planetary Data System	Long-term archive of digital data products returned from NASA's planetary missions, and from other kinds of flight and ground-based data acquisitions. 1
Radio Science Receiver	An open-loop receiver used in NASA's Deep Space Network (DSN) facilities. 2, 3
Radio Science Subsystem	A subsystem placed on board a spacecraft for radio science purposes. 1
Rev number	The number of times the Cassini spacecraft has orbited Saturn. 2

References

Acton, C.
1996. Ancillary data services of nasa's navigation and ancillary information facility. *Planetary and Space Science*, 44:65–70.

Colwell, J., P. Nicholson, M. Tiscareno, C. Murray, R. French, and E. Marouf
2009. The structure of saturn's rings. *Saturn from Cassini-Huygens*, P. 375.

French, R., C. McGhee-French, K. Lonergan, T. Sepersky, R. Jacobson, P. Nicholson, M. Hedman, E. Marouf, and J. Colwell
2017. Noncircular features in saturn's rings iv: Absolute radius scale and saturn's pole direction. *Icarus*, 290:14–45.

French, R., P. Nicholson, M. Hedman, J. Hahn, C. McGhee-French, J. Colwell, E. Marouf, and N. Rappaport
2016a. Deciphering the embedded wave in saturn's maxwell ringlet. *Icarus*, 279:62–77.

French, R., P. Nicholson, C. McGhee-French, K. Lonergan, T. Sepersky, M. Hedman, E. Marouf, and J. Colwell
2016b. Noncircular features in saturn's rings iii: The cassini division. *Icarus*, 274:131–162.

Kliore, A., J. Anderson, J. Armstrong, S. Asmar, C. Hamilton, N. Rappaport, H. Wahlquist, R. Ambrosini, F. Flasar, R. French, L. Iess, E. Marouf, and A. Nagy
2004. Cassini radio science. *Space Science Reviews*, 115:1–70.

Marouf, E., R. French, N. Rapparport, K. Wong, C. McGhee-French, and A. Anabtawi
2011. Uncovering of small-scale quasi-periodic structure in saturn's ring c and possible origin. *EPSC-DPS Joint Meeting*, 265.

Marouf, E., L. Tyler, and P. Rosen
1986. Profiling saturn's rings by radio occultation. *Icarus*, 68:120–166.

Moutamid, M. E., P. Nicholson, R. French, M. Tiscareno, C. Murray, M. Evans, C. French, M. Hedman, and J. Burns
2016. How janus' orbital swap affects the edge of saturn's a ring? *Icarus*, 279:125–140.

Nicholson, P., R. French, and M. H. E. M. J. Colwell
2014a. Noncircular features in saturn's rings i: The edge of the b ring. *Icarus*, 227:152–175.

Nicholson, P., R. French, C. McGhee-French, M. Hedman, E. Marouf, J. Colwell, K. Lonergan, and T. Sepersky
2014b. Noncircular features in saturn's rings ii: The c ring. *Icarus*, 241:373–396.

Rappaport, N., P. Longaretti, R. French, and E. M. C. McGhee
2009. A procedure to analyze nonlinear density waves in saturn's rings using several occultation profiles. *Icarus*, 199.

Thomson, F., E. Marouf, G. Tyler, R. French, and N. Rappoport
2007. Periodic microstructure in saturn's rings a and b. *Geophysical Research Letters*, 34:L23203.