Introduction to rss_ringoccs

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May 8, 2018

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 NASA's 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` is 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`.

[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`.

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 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.

1.2 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**.

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

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 Rev0054 RSS ring occultation.

1.3 Required and recommended reading

With this overview of RSS ring occultations 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:

1.3.1 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*.[3] 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.

1.3.2 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.

1.3.3 For more information...

Readers interested in an overview of Cassini RSS instrumentation and science goals is 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), El Moutamid et al.(2016), French et al.(2016), French et al.(2016), French et al.(2017)] and [Marouf et al.(2011), Nicholson et al.(2014), Nicholson et al.(2014), 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 *Bare-Bones Installation Guide for* `rss_ringoccs`.

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

2.1 System requirements

The rss_ringoccs repository has been developed and tested on the following operating systems:

(Ryan - insert a table here, including GB of RAM)

hoho	haha
HOHO	HAHA

Table 1: Operating Systems

2.2 Install Python 3 and required packages

rss_ringoccs has been tested under both Python 2.x and Python 3.y, but we strongly recommend that users install Python 3, since Python 2.x will not be supported after 20xx. Our code has been tested under the following Python distributions:

hoho	haha
HOHO	HAHA

Table 2: Python Versions

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

```
pip install matplotlib
pip install numpy
pip install pytest
pip install six
```

more here?

2.2.1 Download, install and test spiceypy

rss_ringoccs makes extensive use of JPL's NAIF toolkit [Acton(1996)], a set of software tools to calculate planetary and spacecraft positions, ring occultation geometry, and a host of useful calendar functions.[4] We use the `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`:

```
pip install spiceypy
```

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

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:

```
>>> 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:

```
cd ~/local
unzip ~/Downloads/rss_ringoccs-master.zip}
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

2.4 Run initial tests of `rss_ringoccs`

2.5 Download additional JPL/NAIF kernels

2.6 Download additional raw RSS data files

2.7 Additional tests of `rss_ringoccs`

2.8 Getting help

2.8.1 Jupyter notebooks

Explain that all of our tutorials use Jupyter notebooks - show where to obtain Jupyter.

2.9 Obtaining Cassini RSS data

Describe NASA PDS and locations of two types of files.

2.9.1 Raw RSS data files

Describe RSR files and give link to documentation.

2.9.1.1 16 kHz RSR files

These are available from the NASA PDS Atmospheres Node

2.9.1.2 1 kHz RSR files

These are soon to be available on the PDS Rings and Small Moons (name?) archive - currently under review. One sample file is included in the GitHub repository (true?).

2.9.2 Higher order products

Describe what is on the PDS.

2.10 Obtaining required JPL/NAIF kernel files

Describe file types briefly, and assumed directory structure.

3 Getting Started

Explain where tutorials are and how they are organized. First, you'll test each part of your installation. Then, you'll produce your first ring occultation profile. Next, you'll

3.1 Testing your installation

3.1.1 Python

Show few-line sample python code to ensure that required packages are available.

3.1.2 `spiceypy`

Show few-line sample python code to print pi().

3.1.3 RSS data files

Use script to grab a few RSS data files and store them in the correct subdirectories. Then try rerunning the code to confirm that if you have the files already, it won't bother retrieving them. Say how long it will take to run. If you feel brave and have time, you can run a command to download the complete archive of RSS 16 kHz data files using the following command - best to run this overnight!

3.1.4 JPL/NAIF kernels

Use script to grab JPL kernels and store them in the correct subdirectories. Again, try rerunning the command to show that it recognizes whether the files exist already. Say how long it will take to run.

3.1.5 `rss_ringoccs`: Your first diffraction-corrected ring profile

This version makes use of pre-computed files, to save time.

3.1.6 A tutorial on tutorials - using a Jupyter notebook

Show how to read an existing Jupyter notebook to perform the previous steps.

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 Where To Go From Here

6.1 The Cassini RSS data catalog

6.2 Selecting an RSR file to process

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

6.3 Practical considerations

execution time, SNR, radial resolution, sampling theorem

6.3.1 Benchmarks

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

Table 3: Benchmarks

6.3.2 Potential speed improvements

FFTW
Cython
Algorithms

6.4 Assumptions and limitations

Comment on assumptions of MTR86

6.5 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.

7 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!

7.1 Comparison with independent results on PDS

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

7.1.1 Rev007E

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

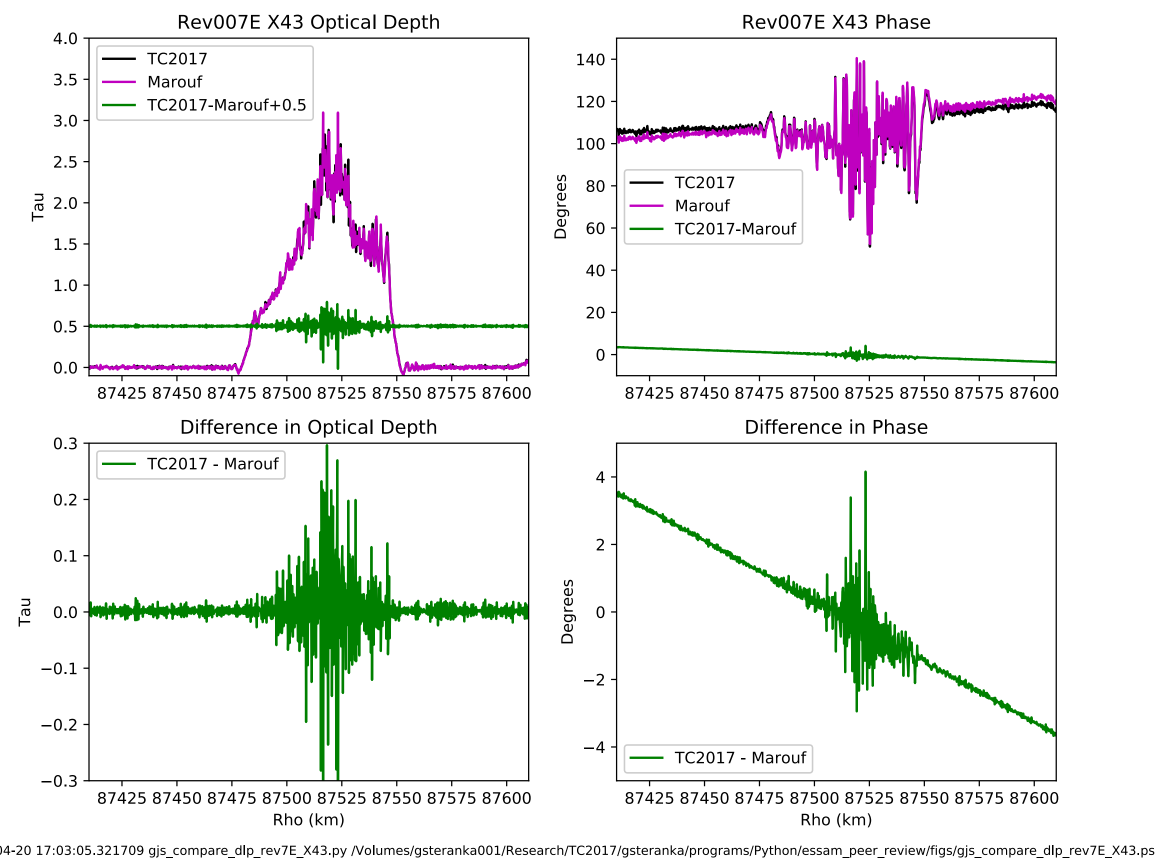


Figure 4: Comparison of rev7E X43 optical depth and phase profiles before inversion

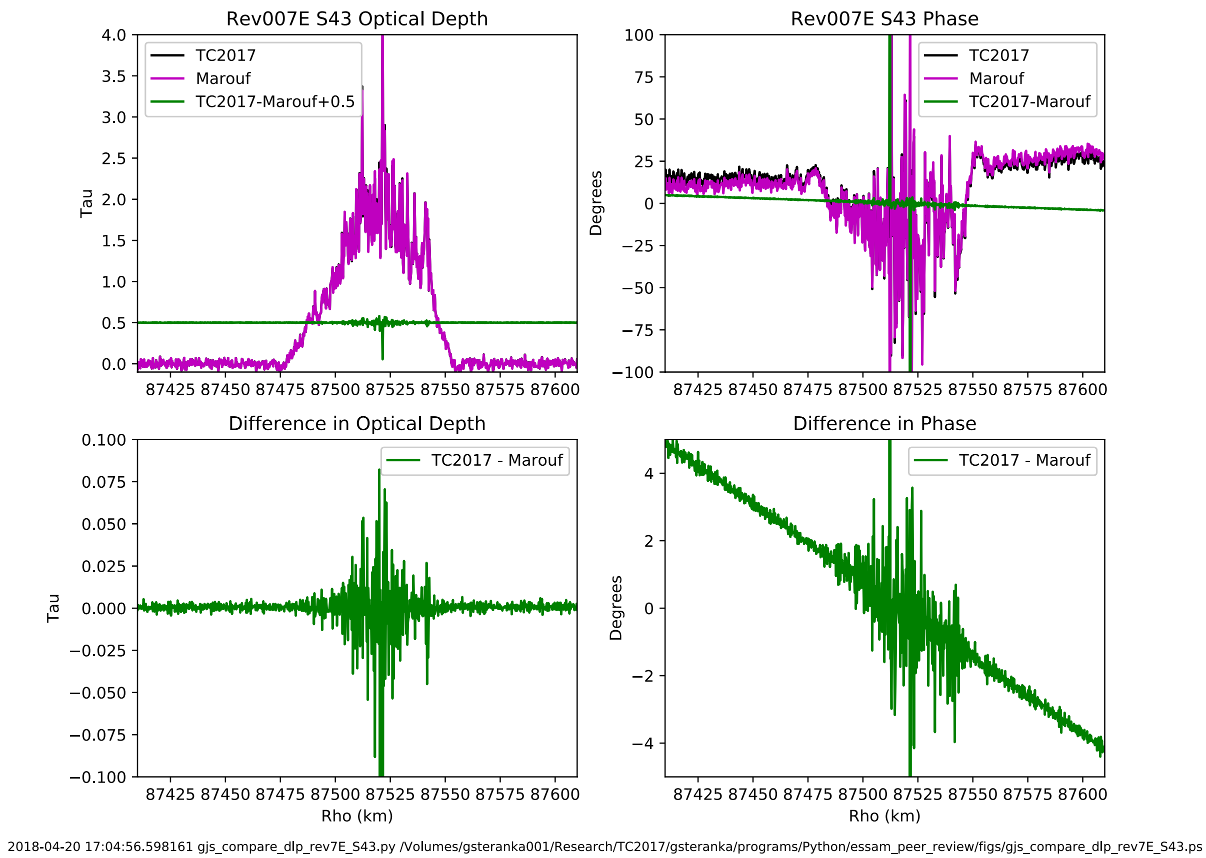
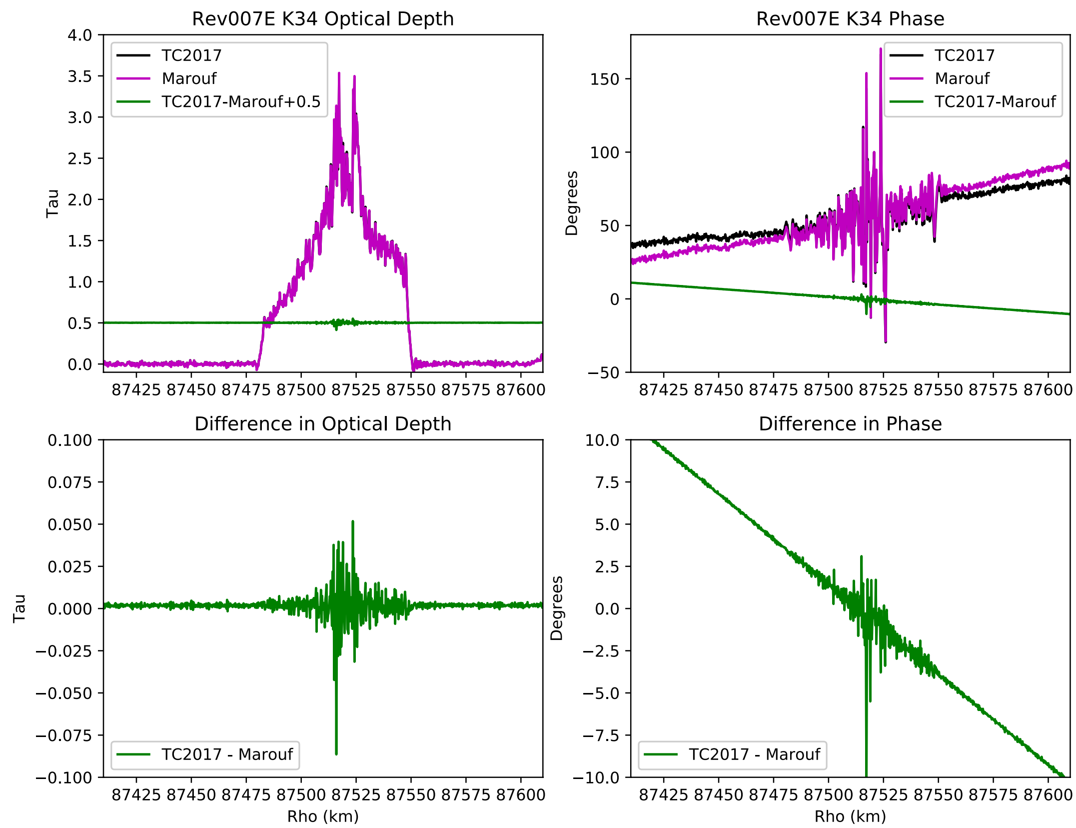


Figure 5: Comparison of rev7E S43 optical depth and phase profiles before inversion



2018-04-20 17:09:36.366190 gjs_compare_dlp_rev7E_K34.py /Volumes/gsteranka001/Research/TC2017/gsteranka/programs/Python/essam_peer_review/figs/gjs_compare_dlp_rev7E_K34.ps

Figure 6: Comparison of rev7E K34 optical depth and phase profiles before inversion

7.1.2 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.

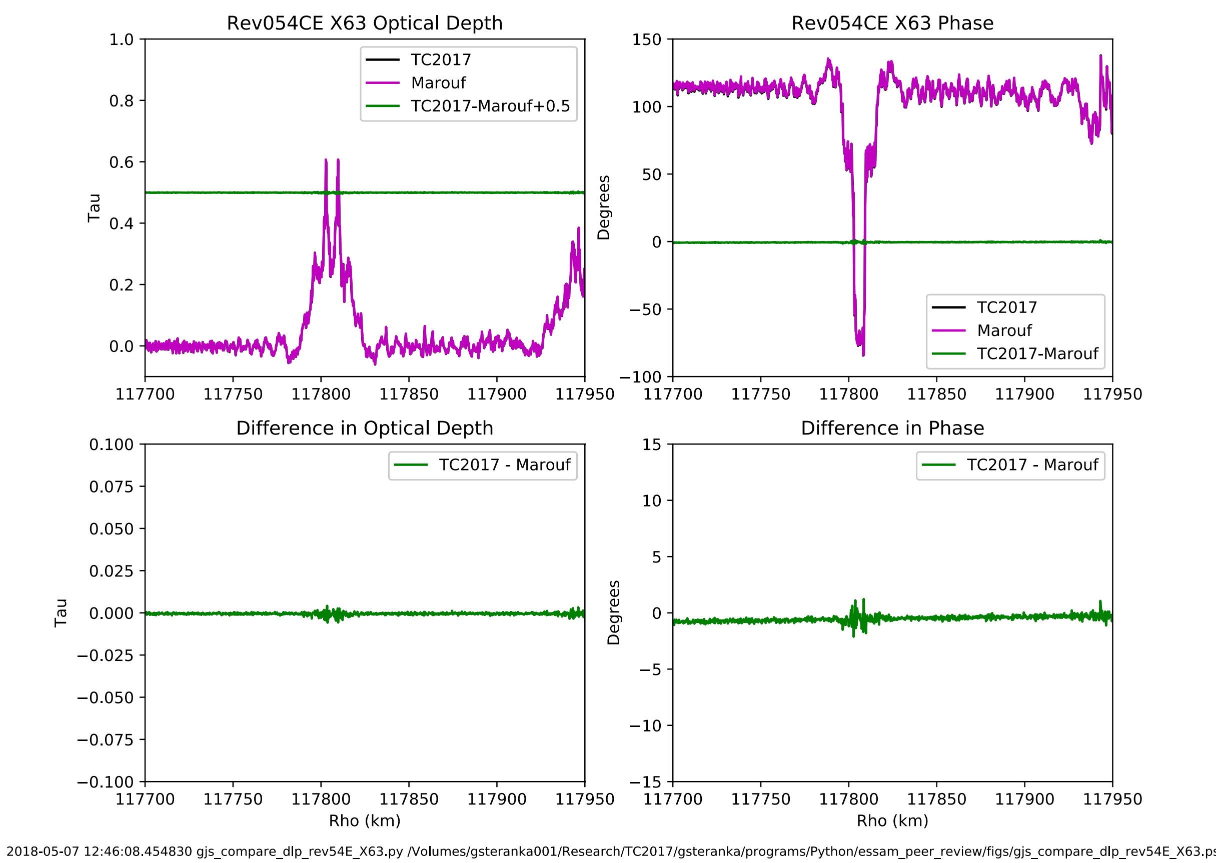


Figure 7: Comparison of rev54CE X63 optical depth and phase profiles before inversion

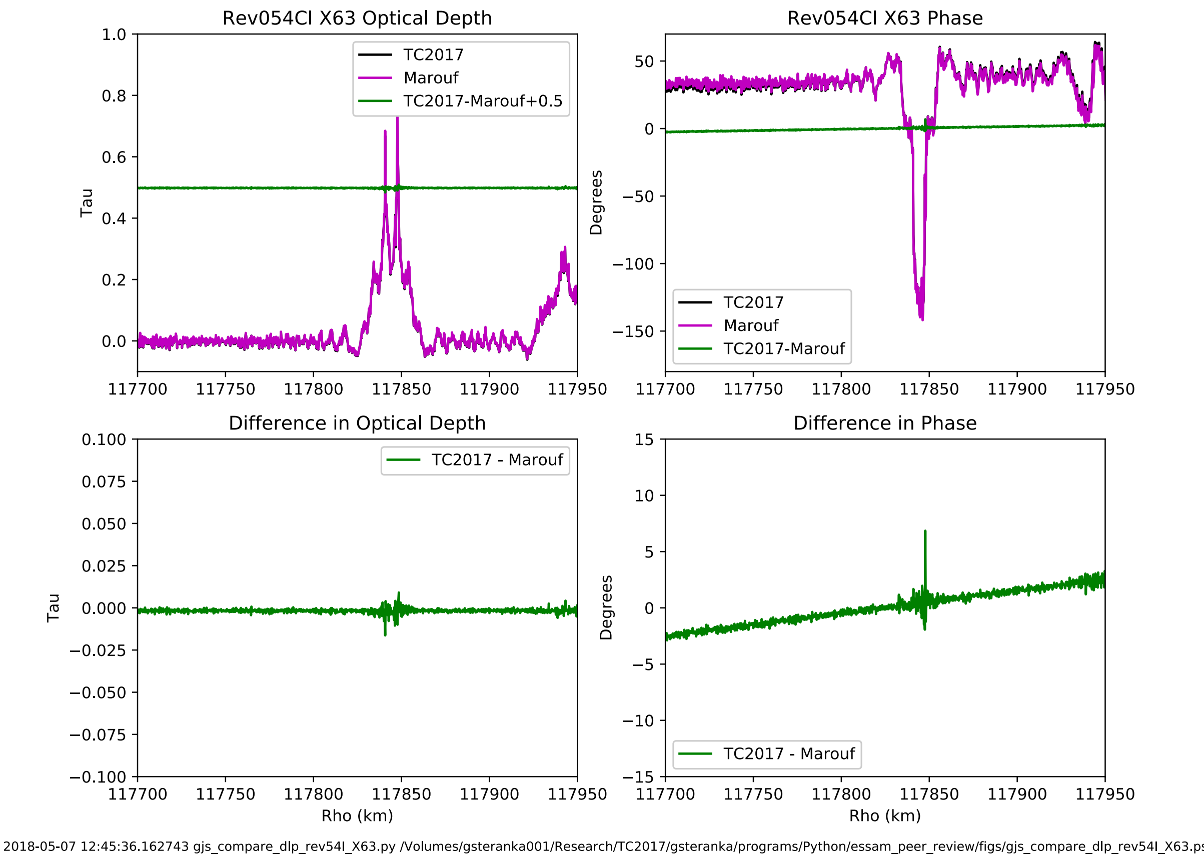


Figure 8: Comparison of rev54CI X63 optical depth and phase profiles before inversion

7.2 Some idealized examples

7.2.1 A simple isolated sharp-edged ringlet

7.2.2 A more complex ringlet - forward and inverse calculations

7.3 Comparison with *Voyager* results

7.3.1 Reproducing MTR86 results for Voyager 2 at Saturn

7.3.2 Reproducing Gresh results for Voyager 2 at Uranus?

8 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.

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