

## **Users' guide for analyzing INMS data on Titan's neutral atmosphere**

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## 1 Introduction

### 1.1 Purpose

The Ion and Neutral Mass Spectrometer (INMS) produces a wealth of data on Titan's atmosphere, but converting those data to physical units is difficult, even for experienced users of INMS data. The factors that affect calibration and that contribute to the difficulty in analyzing INMS data include compensating for the following conditions

- the particular INMS settings,
- Cassini's velocity and attitude,
- different density regimes,
- multiple molecular species measured at each mass channel,
- the effects due to previous exposures, and
- adjusting the calibrations for conditions that cannot be reproduced in the lab.

In this guide, we describe approaches for dealing with these difficulties and have included significant references and description of resources in Section 5. The intent is for this document to provide sufficient insight and instructions for analyzing INMS neutral data from Titan that users can perform their own research. There is a separate guide for analyzing INMS data on Titan ions.

This guide contains example analyses, including computing a mass spectrum and calculating the time-dependent densities of the major species. Extracting minor species from INMS data is a time-consuming, difficult task that requires creativity and science insight. For the investigator interested in analyzing the minor species at Titan, this document provides references to papers that describe different approaches.

INMS data are stored at the Plasma Planetary Interactions (PPI) node of the Planetary Data System (PDS). A separate users' guide describes the PDS, how to locate INMS data, and how to download those data for processing locally.

In the future, the INMS team intends to archive processed data, which will mitigate some of the need for the analyses described in this document.

### 1.2 Overview of this document

Section 2 contains a step-by-step discussion of how to analyze INMS measurements of neutrals in Titan's atmosphere. The discussion includes detailed examples that can be replicated. The section includes a description of how to convert INMS counts to atmospheric density. In following these steps, researches can begin to acquire the knowledge and build the competency required for independent analyses and use of the data.

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The INMS team uses the IDL software package extensively for data analyses, and the INMS analysis routines or programs are available to the public. (Users require an IDL license to run the routines. However, the IDL programs are text files with .pro extension and can be read with any text editor.) The analysis steps are described independent of IDL, and examples use both IDL routines and non-proprietary software. The examples in this guide use data from either the fifth Titan pass, T5, or the thirty-second Titan pass, T32.

Section 3 provides two detailed examples: producing a mass spectrum and an altitude history of the major species.

Section 4 reiterates several potential analysis problems, each of which was discussed in detail in Sections 2 or 3.

Section 5 and the appendices contain references and additional reference material.

### **1.3 Overview of the INMS instrument**

The Cassini INMS investigation measures the mass composition and number densities of neutral species and low-energy ions in key regions of the Saturn system. The primary focus of the INMS investigation is on the composition and structure of Titan's upper atmosphere and its interaction with Saturn's magnetospheric plasma. Of particular interest is the high-altitude region, between 900 and 1000 km, where the methane and nitrogen photochemistry is initiated that leads to the creation of complex hydrocarbons and nitriles that may eventually precipitate onto the moon's surface to form hydrocarbon–nitrile lakes or oceans. The investigation is also focused on the neutral and plasma environments of Saturn's ring system and icy moons and on the identification of neutral species in the plume of Enceladus.

The INMS instrument consists of a closed neutral source and an open ion source, various focusing lenses, an electrostatic quadrupole switching lens, a radio frequency quadrupole mass analyzer, two secondary electron multiplier detectors, and the associated supporting electronics and power supply systems. The follow sections provide background information on the instrument; Waite *et al.* (2004) provides a full description of INMS.

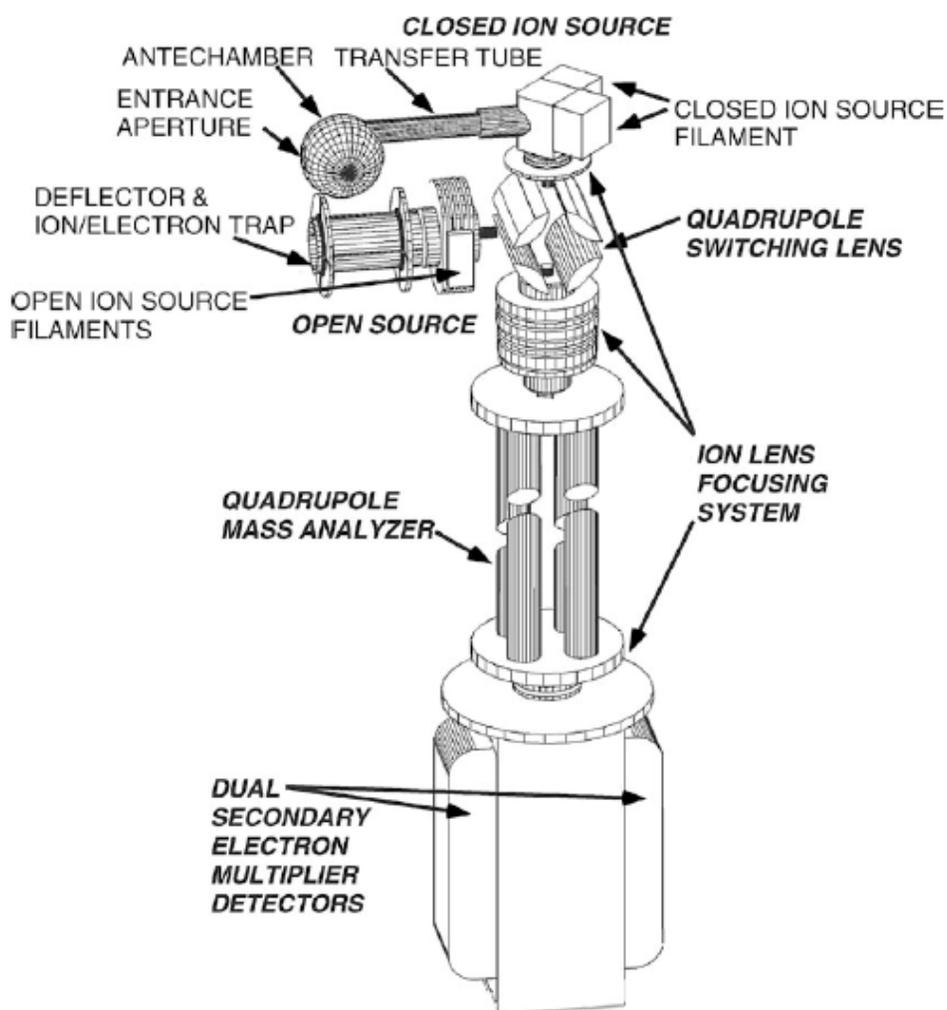
#### **1.3.1 Instrument orientation on Cassini**

In the Cassini coordinate system, INMS is located on the  $-X$  side of the spacecraft coordinate system. The INMS aperture points in the  $-X$  direction. There are no spacecraft components within 90 degrees of the INMS aperture, so there are no obstacles in the INMS field of view. When INMS has priority for pointing, Cassini rotates so that the INMS aperture is in the desired direction, which is oriented so that the velocity of the particles to be measured is directly into the INMS aperture. This is the ram direction for the desired particles. When INMS does not have pointing priority, the INMS can still gather useful neutral data if the INMS aperture is pointed within 60 degrees of the ram direction.

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### 1.3.2 Operational modes

The INMS has three modes of operations, the Open Source Neutral Beam (OSNB) mode for measuring reactive neutrals such as atomic nitrogen, the Open Source Ion (OSI) mode for measuring positive ions with energies less than 100 eV, and a Closed Source Neutral (CSN) mode for the measurement of non-reactive neutrals such as  $N_2$  and  $CH_4$  (Waite *et al.*, 2004). Most of the analyses described in this guide use the CSN mode, which is more sensitive than the OSNB mode, and less affected by changes in velocity. The INMS instrument has a mass range of 1–99 Daltons and a mass resolution  $M/\Delta M$  of 100 at 10% of the mass peak height, which allows detection of heavier hydrocarbon species and of cyclic hydrocarbons such as  $C_6H_6$ .



**Figure 1.** Schematic of INMS showing the major components.

In the CSN mode, the neutral molecules enter an antechamber where the ram pressure increases the antechamber density compared to the ambient density by a factor of 10 to 85, depending on the mass of the neutral molecule, the ram speed, and the angle of the aperture with respect to the ram direction (Waite *et al.*, 2004). The CSN sensitivity is highest when the entrance aperture is in the ram direction, and falls off as the cosine of the

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angle, primarily due to the smaller projected aperture in the direction of incoming particles. Section 2.2.4 quantifies the effect of ram pressure.

The INMS measures one mass at a time. In the open source modes (OSNB and OSI), only one particle velocity is measured at a time. In the closed mode (CSN), neutrals that enter the antechamber are quickly neutralized and there is no need to specify the velocity of the particle with respect to the spacecraft during measurement (Waite *et al.* 2004). In each measurement period, INMS counts the number of particles with the specified mass. This measurement period is the integration period, IP.

### 1.3.3 Measurement parameters

INMS makes a measurement every 34 ms. The duration of the counting period (the IP) is 31 ms. A table of masses specifies which mass to measure during each IP. This mass table contains 68 entries, which are measured in sequential order during each pass through the mass table. Often, important masses have several entries in a single mass table so that they are measured more often than once every 68 measurements. During most observations, INMS alternates between two mass tables for the CSN mode, and a complete mass spectrum includes at least one pass through each of the mass tables. The figure below shows one of the mass tables used to determine which neutrals were measured during the T5 encounter. There are separate mass tables for the other instrument modes, and a single time period may contain ten or more mass tables, only a few of which are of interest when analyzing neutral data.

IP	Mass	IP	Mass	IP	Mass	IP	Mass
1	1	18	18	35	14	52	45
2	3	19	19	36	15	53	46
3	4	20	20	37	16	54	47
4	5	21	21	38	17	55	48
5	2	22	22	39	27	56	49
6	12	23	23	40	28	57	50
7	13	24	24	41	29	58	51
8	14	25	25	42	35	59	2
9	15	26	26	43	36	60	12
10	16	27	30	44	37	61	13
11	17	28	31	45	38	62	14
12	27	29	32	46	39	63	15
13	28	30	33	47	40	64	16
14	29	31	34	48	41	65	17
15	6	32	2	49	42	66	27
16	7	33	12	50	43	67	28
17	8	34	13	51	44	68	29

To reduce the downlink volume, data samples with the same mass can be summed or binned on the spacecraft before transmission to the ground. The *coadd\_cnt* variable determines the amount of on-board binning. For most Titan passes, *coadd\_cnt*=1, which means that there is no on-board binning, and the data provide the maximum temporal and spatial resolution. When far from Titan, a typical *coadd\_cnt* is 15, which reduces the downlink data volume by approximately a factor of 15. Data from 15 passes through each

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mass table are added together, IP by IP, preserving mass resolution but sacrificing temporal resolution.

### 1.3.4 Cracking pattern and molecular products

INMS usually produces counts in several different mass channels in response to a single type of molecule entering the CSN antechamber. Most counts are usually measured in the mass corresponding to the molecular mass, but the ionization process may create other masses.

After passing through the antechamber and the transfer tube (see figure in Section 1.3.5), neutral molecules enter the ionization chamber and are ionized by a 70-volt electron beam. The ions are then diverted and accelerated through the mass analyzer to the detector where they are counted. During the ionization process, the electron beam may dissociate the molecule. For example, when  $N_2$  is ionized, there is about 1  $N^+$  ion (mass 14) created for every 30  $N_2^+$  ions (mass 28) created. The number of additional ion products and their probability relative to the primary ion is called the cracking pattern. This cracking pattern is measured in the laboratory and, in some cases, verified in flight. If the molecule contains multiple isotopes, then the isotopic variations are evident in the cracking pattern, too. Continuing with the example of  $N_2$ , the laboratory cracking pattern for  $N_2$  reflects the presence of  $^{14}N^{15}N$  and has components at mass 15 ( $^{15}N^+$ ) and mass 29 ( $^{14}N^{15}N^+$ ).

The dissociative products and isotopic variations, quantified by the cracking pattern, add complexity when attempting to extract the minor-species composition of the measured neutrals. Although major species dominate their respective mass channels, other mass channels are composed of the cracking products of the major species and multiple minor species. Later sections describe techniques for de-convolving the neutral composition from the mass spectrum.

### 1.3.5 Wall interactions

About 8% of the molecules that enter the CSN aperture reach the ionization chamber; the other molecules escape through the entrance aperture (Teolis *et al.*, 2010). The particles measured by INMS in the CSN mode experience on the order of 100 collisions with the chamber walls prior to being ionized and measured by the INMS. The INMS count rate for materials that are easily adsorbed onto the surface of the antechamber may not accurately reflect the external density.

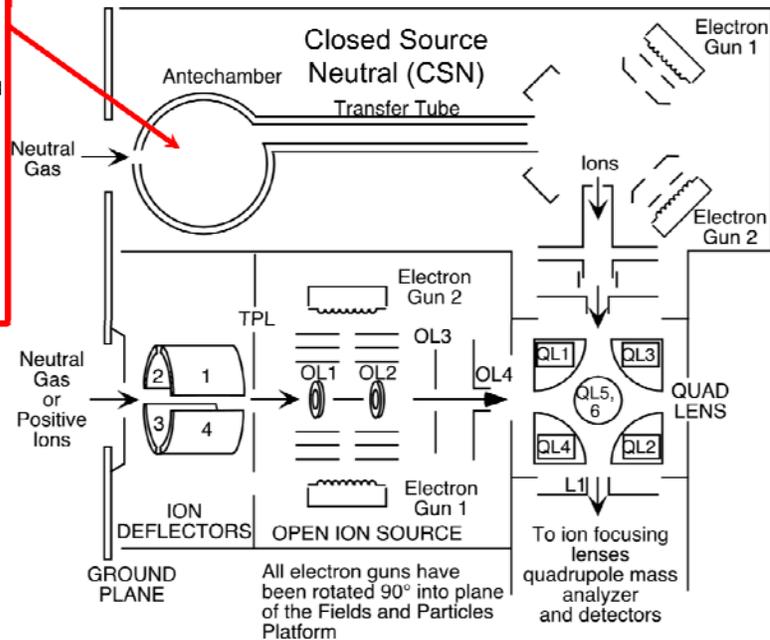
**Two inlets:**

- **Closed source (CSN) measures neutral densities**
  - **Wide FOV**
  - **Sensitive (ram enhanced)**
  - **Wall interactions**
    - **No reactive species (OH, N, metals, etc.)**
    - **Water signal delayed**
    - **Dissociation**
- **Open source measures ion and neutral densities**
  - **Narrow FOV (2° radius)**
  - **Measures one narrow (1 km/s) velocity range at a time**

**Quadrupole mass spectrometer**

**Mass range: 1-8, 12-99 AMU**

**Mass resolution: 1 AMU**



*Figure 2* Diagram of the INMS inlet system. All published INMS research on Titan neutrals uses measurements obtained using the CSN mode.

**1.4 The INMS team**

Hunter Waite, at Southwest Research, Inc. (SwRI) in San Antonio, is the Principal Investigator for INMS. There are about eight scientist co-investigators in academic institutions around the United States, Japan, and Europe. At SwRI, there are additional operators, engineers, and scientists working to operate INMS, archive the data, improve the calibration, and analyze the data.

**2 Introduction to analyzing INMS neutral data from Titan**

**2.1 INMS data**

**2.1.1 Locating and downloading INMS data for local processing**

A separate users’ guide describes how to locate INMS data and how to download data and processing routines.

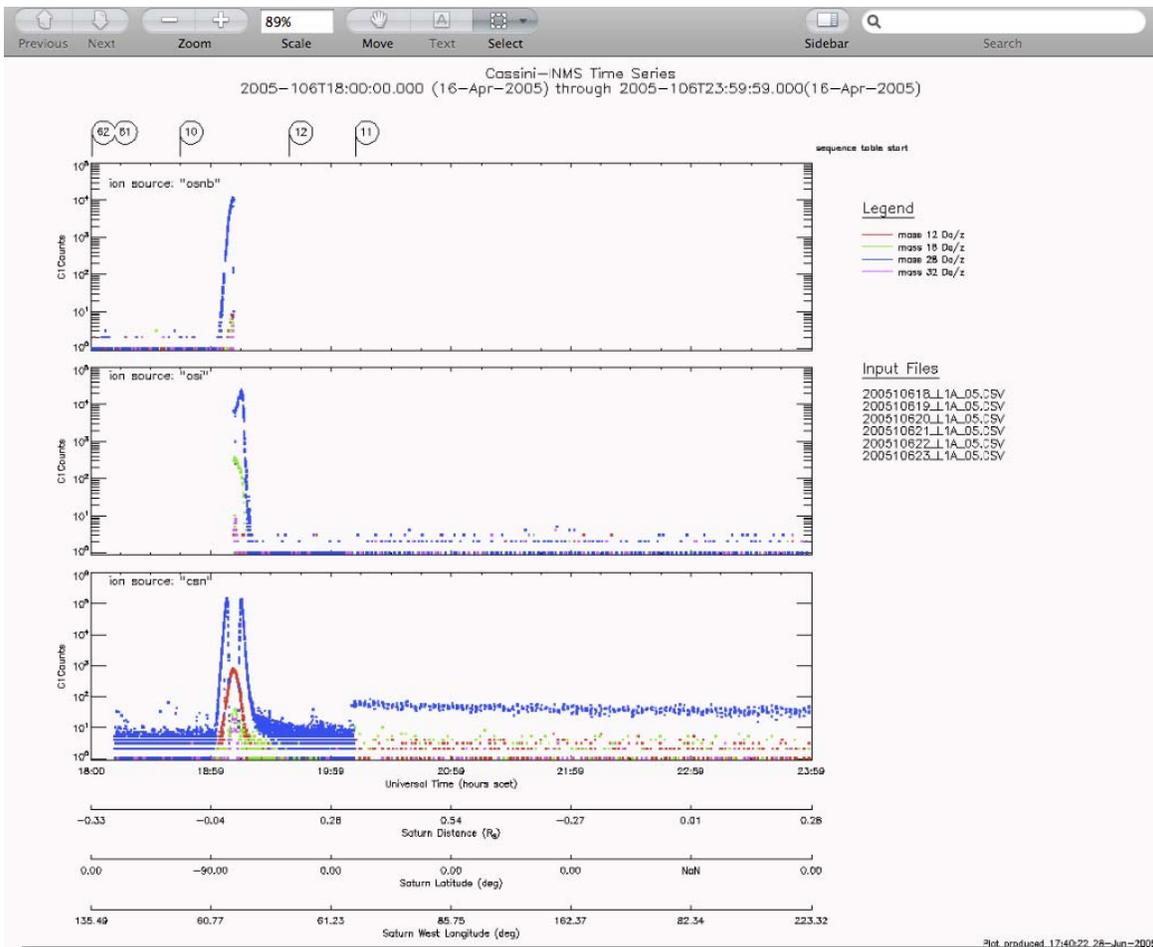
**2.1.2 Example overview plots**

Examples of the two types of overview plots are shown in the next two figures. These plots are available from the INMS BROWSE directory (see the INMS PDS users’ guide) or by IDL processing of the data as described in Section 2.2.3. The plots are both for the T5 pass.

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The first plot, the line plot, shows several important aspects of Titan data:

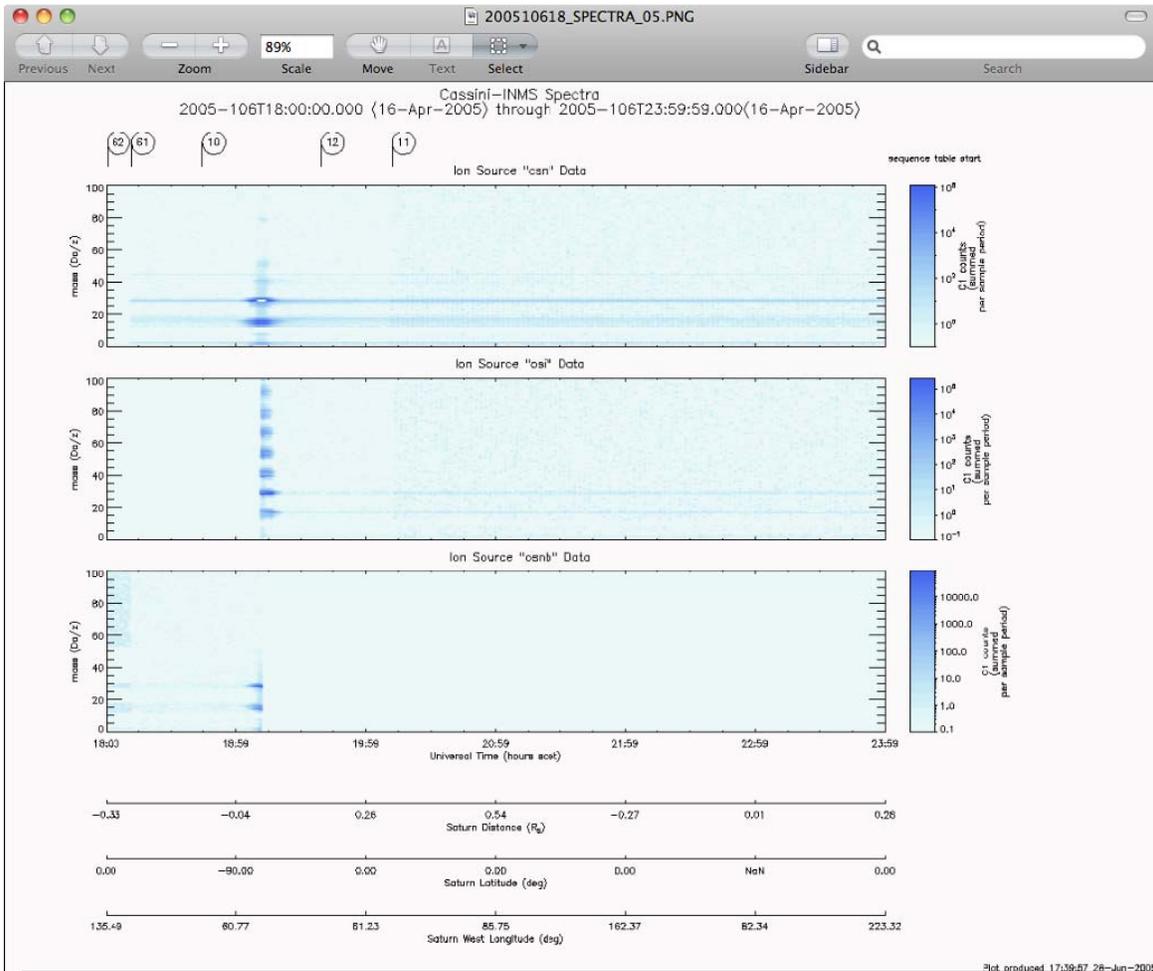
- a) INMS operated in all three modes during T5: CSN, OSNB, and OSI (see Section 1.3.2 for a definition of the modes). Since OSNB and OSI share an aperture, only one can operate at a time. For this pass, INMS operated in the OSNB (top plot) until about 19:07, and then INMS operation switched to the OSI mode (second plot).
- b) As with most Titan passes, N<sub>2</sub> saturated in the CSN mode. The counts at mass 28, saturate and cause a dip in the CSN signal during deepest penetration into Titan’s atmosphere. Section 3.1 describes approaches for extracting densities during saturated operations.
- c) The character of the CSN signal changes due to an increase in binning at 20:12. Before this time, *coadd\_cnt*=1, which means no binning of the data on board the spacecraft. After 20:12, *coadd\_cnt*=15, which means that each measurement is the sum of 15 individual IPs.



**Figure 3.** A summary plot of INMS measurements during T5, the fifth Cassini encounter with Titan.

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This second BROWSE plot is the mass-spectrum plot which shows all masses, but with less resolution in the count rates.



**Figure 4** A second summary plot of T5. This plot shows all the masses but in less resolution. The horizontal axis is labeled in four different units: time (UTC), distance from Saturn ( $R_S$ ), Saturn latitude (degrees), and Saturn longitude (degrees west). All four of these units can be plotted with respect to Titan.

### 2.1.3 Structure of INMS data

The INMS data files are simple lists of comma-separated variables. This is the L1A file in INMS nomenclature and represents data that are processed to level 1A, which means that these are raw data that are not calibrated and have no other corrections. Each row of the L1A file contains 76 parameters and measurements that are associated with one piece of INMS data. If the co-add count was 1, then the row contains relevant information for that single IP. If the co-add count was higher, then the row contains relevant information for the sum of the IPs. Since INMS can take one measurement every 34 ms, the one-hour data file may contain more than  $10^5$  rows and be greater than 50 MB in size.

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The first row of each L1A data file contains the names and units for each parameter, and the first appendix (Section 6.1) contains a list of all 76 parameters that are included with each measurement. The first line of each L1A data file begins with

```
sclk, uttime, target, time_ca, targ_pos_x, targ_pos_y, targ_pos_z, source,
```

with an additional 68 parameter names that follow. Then there are two more rows of text that contain the measurement units of each of these parameters.

The rest of each data file are rows of values, one for each measurement or each group of measurements summed on the spacecraft. An example, using data from a few days before T5, is

```
2005-100T09:00:09.816,32409816,,,,,"osi",
```

In this example, all the target-related data (target name, time of closest approach, position relative to the target) are blank because there was no target identified for this observation.

Another example, which is from the data for the T5 flyby, has Titan as the target, and the first eight values are

```
2005-106T19:00:01.302,68401302,"TITAN",-704758,609045,1087726,-412,
"csn"
```

## 2.2 INMS analyses

### 2.2.1 Downloading IDL routines developed for INMS

The entire INMS IDL library can be downloaded, as described in the INMS PDS users' guide.

### 2.2.2 Importing INMS data into IDL and other programs

All analysis programs, including IDL, MATLAB, and Excel, can import data from CSV files. Some of the examples use data from T5 and others use data from T32.

#### *Importing into IDL*

When using IDL, the best way to read the data is to use the *inms\_get\_data* routine. It prompts for the location and name of the data files and then stores the data in a local structure variable that provides quick access to all L1A data for processing or graphing. The command is as simple as *inms\_get\_data, output\_var*, where the parameter is the name of the local variable that will contain the L1A data. The AnalysisGuide provides the syntax and function of optional parameters and describes the output structure variable. The names of the structure fields are the same as the names of the L1A variables, listed in Appendix 6.1.

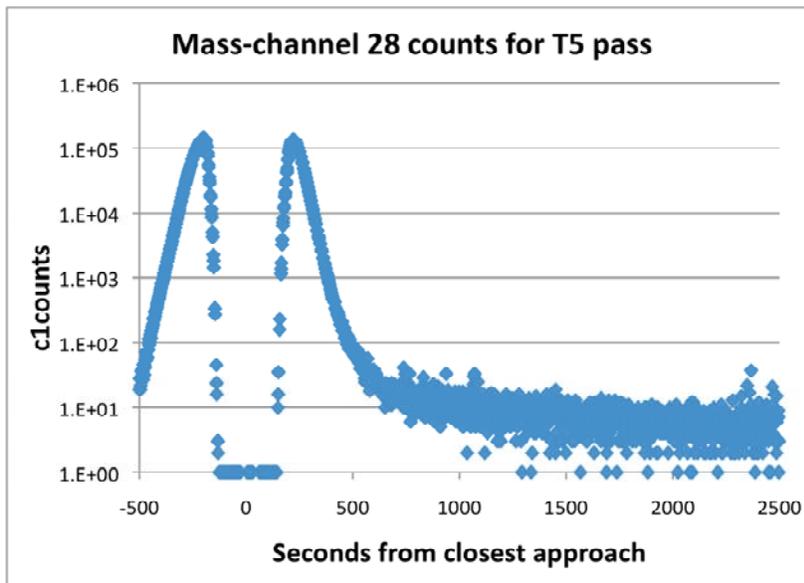
[Type text]

The output of *inms\_get\_data.pro* is a structure variable with the first parameter specifying the variable name (*output\_var*). The output variable name *axData* is common throughout INMS documentation of IDL routines for the name of the structure variable of L1A data. This structure variable has 76 fields, each representing one of the fields in the original L1A data files. For example, the number of counts in the high-sensitivity detector for the  $n^{\text{th}}$  measurement is stored in the structure variable *axData[n-1].c1counts*. (IDL indices start at 0, so the index for the  $n^{\text{th}}$  measurement is  $n-1$ .)

### *Importing into Excel*

Although the Microsoft Excel spreadsheet program is not designed to manipulate large arrays, it can import and manipulate INMS data. As an example, the figure, below, is the mass-channel-28 data during the T5 pass plotted using Excel. After opening the CSV file with Excel, the size of the spreadsheet can be reduced by deleting most of the 76 columns. The file contains over  $10^5$  rows for the one hour of data starting at 19:00 on day 106 of 2005. By deleting all data that are not CSN (sort on the “source” column and delete all “osi” “osnb” etc. rows), the file is reduced to 50,000 rows. If there are only a few masses of interest, then the data can be sorted by mass and only the desired masses retained. For this plot, only mass-channel=28 data were retained, reducing the number of rows to approximately 2,000. The plot is an XY scatter plot (Excel nomenclature) of the *C1COUNTS* data (second-to-last column) vs. *time\_ca* (the time from closest approach). The time data are in milliseconds and were divided by 1,000 to get seconds from closest approach.

For calculations involving a few masses over periods of less than an hour, Excel may have some utility; however, more powerful analysis programs such as IDL and MATLAB usually are required for analyzing INMS data.



**Figure 5** Example of INMS data plotted using spreadsheet graphics.

[Type text]

### 2.2.3 Analyzing INMS data using IDL tools

The IDL routines provide the capability to do high-level analysis of the INMS data. Most of the IDL routines have several input parameters that enable tailoring the analysis. If researchers want additional plots or analyses, they can examine the individual IDL routines, which are text files with \*.pro extensions. Researchers can inspect, modify, and extract the individual commands that perform the analyses and create the plots.

The following commands create the two browse plots in Section 2.1.3:

- a) *inms\_get\_data*, *output\_file*, *files=['L1A\_input\_file1', 'L1A\_input\_file1']*  
 In the analysis guide, the *output\_file* is usually named *axData*, and we will use that name for the rest of this example. Without specifying the input data files, which are L1A files, a dialog box will open and ask you to select the file. There are several parameters that can be supplied to identify the input data files; details are in the IDL analysis guide. The names of the data file required for the T5 6-hour browse plots are 2005106tt\_L1A\_05.CSV, where “tt” represent 18, 19, 20, 21, 22, and 23, which are the hours in the plots. The associated label file and the format file, L1A\_STRUCT\_05.FMT, must be in the same local directory as the data files.
- b) *inms\_get\_data*, *axHKG*, *file=housekeeping\_file*, *type='HKG'*  
 This command ingests the housekeeping data. The filename is 200510600\_HKG\_01.CSV, one for each day of operations. The format file, HKG\_STRUCT\_01.FMT does not change very often, and it should be in the same local directory as the housekeeping data file.
- c) *inms\_plot\_mt\_line*, *axData*, [12, 18, 28, 32]  
 The numbers in brackets are the masses of the desired species. See the IDL analysis guide for additional plotting parameters such as restricting to CSN data, only.
- d) *inms\_plot\_mt\_spectra*, *axData*, */target*  
 This creates the mass-spectra time-history plot.

To compute and display a mass spectrum:

- a) *inms\_query\_L1a*, *axData*  
 This command prints out several parameters relating to the data stored in the structure *axData*, including the mass table IDs and the coadd count, which is 1 for most Titan passes. The mass table IDs are required for the next step, and this query is the easiest method for identifying the mass tables used for the CSN observations. Alternatively, *inms\_plot\_state*, *L1A\_filename*, *table='mt'* plots the mass tables used during the time of the L1A data file. This helps sort between the mass tables used in the CSN mode and mass tables used for observations in other modes.
- b) *inms\_get\_spectra*, *axData*, *axSpec*, *source='csn'*, *masstableid=[46, 47]*, *alt\_t=[0.0, 2.0e3]*  
 The input data are in *axData*, which was built using *inms\_get\_data.pro*, as described in step 1, above. The output file is an IDL structure variable, *axSpec*, which can have any legal IDL parameter name. Use the mass table IDs determined from the previous step. The *alt\_t* parameter, which limits the spectrum to the data around close approach, is an example of optional parameters that can select specific data. This routine takes all the measurements that meet the criteria and calculates the count rate in counts/IP for each data set (each pass through the complete mass table of 68

[Type text]

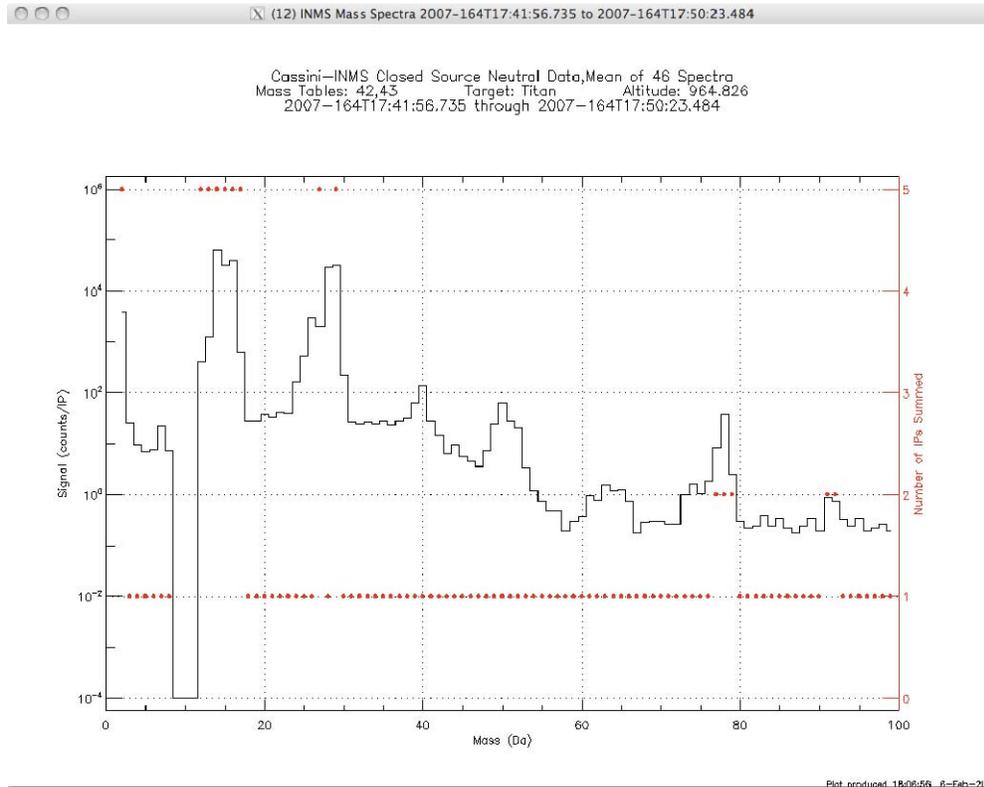
individual measurements) during the selected period. For T5 hour 19, which includes close approach, CSN measurements below 2,000 km use mass table IDs 46 and 47. For T32 at close approach, mass tables 42 and 43 were used. The structure variable, *axSpec*, contains 29 fields for each spectrum, including UTC time, time relative to close approach, the altitude, and the count rates for each mass bin for each spectrum. These can be examined and plotted individually. For example, *plot, axspec.ntimeca/1000., axspec.nalt\_t* plots the altitude vs. time from close approach in seconds, and *plot, axspec.anc1counts[1]* plots the counts in the high-sensitivity detector for mass channel 2. You can verify that this is the correct mass with the command *print, axspec[0].anmassbins[1]*, which will print a “2” indicating that the index [1] represents particles with a mass of 2 AMU.

c) *inms\_compute\_mean\_spectra, axSpec, axMean*

*axSpec* is the structure-variable name from *inms\_get\_spectra* in the previous step. The output, the variable named by *axMean*, is a single mass spectrum that is the average of all the mass spectra in the input spectra, the variable *axSpec*. The structure *axMean* has the same components as *axSpec* but *axMean* has only one spectrum, which is the mean of all the spectra in *axSpec*.

d) *inms\_plot\_histogram, axMean*

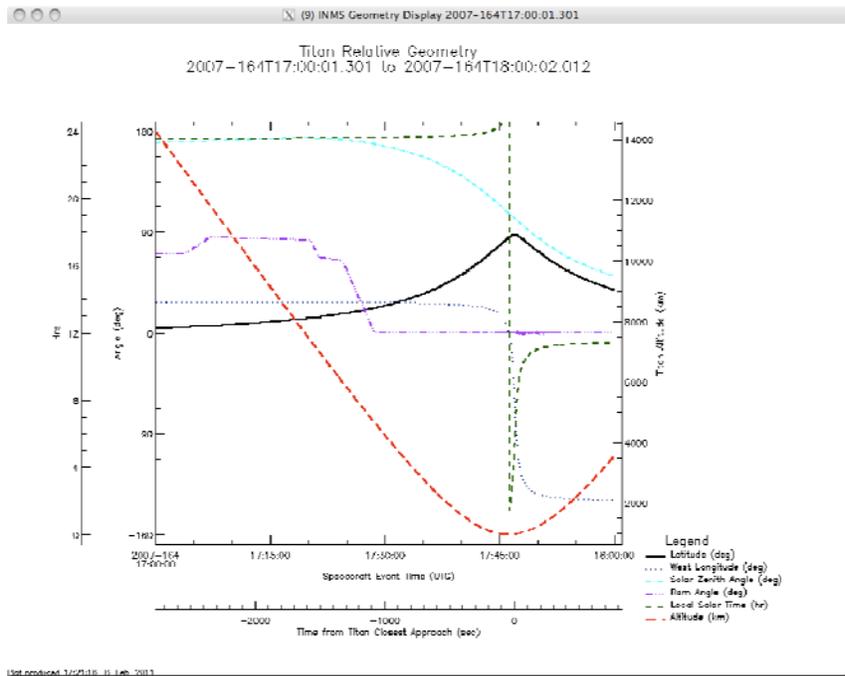
This routine plots the average count rate, in counts/IP for the data specified by the *inms\_get\_spectra* routine. The default plot includes error bars for each mass and the number of IPs in the mass table for each mass. The example plot, below, is for T32, hour 17, with mass tables 42 and 43 specified in *inms\_get\_spectra*.



**Figure 6** An example histogram plot of T32 data using IDL routines.

[Type text]

Another useful plotting routine is `inms_plot_geom, axData`, which plots several variables related to the parameters of the flyby. The following plot is an example for T32, hour 17. This plot includes altitude, latitude, longitude, and the ram angle. The altitude shows the time of closest approach, the latitude and longitude show that this was a pass over the north pole, and the ram angle shows that sensitivity was poor initially and very good starting 1,000 seconds before closest approach.



**Figure 7** This example plot, also using IDL routines, displays the geometry of the T32 flyby.

The IDL AnalysisGuide provides details on these and other analysis routines. The IDL AnalysisGuide includes examples for each command and a description of each parameter. Some of the most useful routines are in the IDL program in `inms_test.pro`, which contains a wealth of additional examples. Users can examine the program and identify the commands that create each of the test plots, and then tailor them for their own use.

#### 2.2.4 Details of converting counts to densities

There are no calibrated INMS data on the Cassini PDS site. All INMS data files contain raw counts, not calibrated densities. This section describes how to convert the raw counts into particle density.

##### *INMS sensitivity*

The INMS sensitivity coefficients that are used to convert counts rates to density are in the file `2004001_CAL_0n.CSV` (see the INMS PDS users' guide for the location of this file in the PDS). These sensitivity coefficients,  $S$ , have units of counts/s/cm<sup>3</sup>/molecule and indicate INMS response to a fixed ambient density. The calibration file contains entries for each possible mass channel that may be measured by INMS for a given molecule. For example,

[Type text]

when the electron beam ionizes  $N_2$  in the ionization chamber, there are four possible products with different mass-to-charge ratios:

- 28: singly-ionized  $^{14}N_2$
- 29: singly ionized  $^{14}N^{15}N$
- 14: a combination of doubly-ionized  $^{14}N_2$  and a singly-ionized N atom that was dissociated from the  $N_2$  molecule
- 15: singly ionized  $^{15}N$  that was dissociated from the  $^{14}N^{15}N$  molecule

Thus, the entry for  $N_2$  in the calibration file has four entries, one for each of these possible products, called cracking products (see Section 1.3.4). The sensitivity coefficient,  $S$ , in the table applies to the most common cracking product, which is mass-channel 28 for  $N_2$ . Each of the other cracking products have a fraction, usually between  $10^{-3}$  and  $3 \times 10^{-2}$ , which represents the ratio of that cracking product to the most common product. For  $N_2$ ,  $S$  is  $6.29 \times 10^{-4}$  counts/s/cm<sup>3</sup>/molecule for mass-channel 28. The cracking ratio for mass-channel 14 is 0.0277, which indicates that for every count at the most-common cracking product, mass-channel 28, there will be 0.0277 counts at mass channel 14. At low count rates, there are counts only in the primary mass channel. For the primary species,  $H_2$ ,  $CH_4$ , and  $N_2$ , most of the counts in the primary mass channel, 2, 16, and 28, respectively, are due to the primary species.

The sensitivity coefficients are based on pre-flight ground testing with the flight INMS and ongoing ground testing with an engineering model that closely replicates the flight unit. Even with extensive, tedious, and pragmatic testing, INMS sensitivity is still uncertain due primarily to two factors: INMS's sensitivity to internal voltage settings and the unavoidable difference between test conditions and flight conditions, specifically the difference in velocity and the inability to safely test some species such as HCN in the lab. The sensitivity and other calibration factors specified on the PDS site are the best available and may be adjusted in the future if additional testing and analyses indicate new values are more accurate. Additional information on the calibration is in the Waite et al. 2004 instrument paper and the flight calibration papers, which will be published in early 2012.

The sensitivity values are for the high-sensitivity detector. The high-sensitivity detector can be saturated at high densities, so the INMS also has a low-sensitivity detector to extend dynamic range. The high-sensitivity counts are in the parameter *C1COUNTS* and the low-sensitivity counts are stored in *C2COUNTS*. Section 3 describes how to use the high-sensitivity counter when the low-sensitivity counter is saturated.

#### *Ram enhancement*

In the CSN mode, the high velocity of molecules entering the antechamber causes a build-up of molecules inside the antechamber, increasing the pressure. This ram pressure also increases the pressure in the transfer tube and the ionization chamber, which increases the count rate. The ram enhancement in count rate depends on the velocity, ambient temperature, and incident angle. The ram-enhancement factor,  $C_{RAM}$ , is

$$b = \frac{v \cos(\theta)}{\sqrt{2 \times 10^3 k T_a \left( \frac{N_A}{m} \right)}}$$

$$C_{RAM} = \sqrt{\frac{T_a}{T_i}} \left( e^{-b^2} + b \sqrt{\pi} [1 + \text{erf}(b)] \right)$$

Where  $v$  is the velocity of the spacecraft relative to the ambient atmosphere in m/s,  $\theta$  is the ram angle (the angle of the instrument aperture with respect to the velocity vector),  $k$  is the Boltzmann constant,  $N_A$  is the Avogadro number,  $m$  is the atomic mass of the measured particle,  $T_a$  is the ambient temperature (150 Kelvin is appropriate for Titan),  $T_i$  is the instrument temperature (use 300 Kelvin), and  $b$  is an intermediate result.

The density,  $\rho$ , in molecules/cm<sup>3</sup>, is then

$$\rho = \frac{N}{C_{RAM} S t_{IP}}$$

Where  $N$  is the adjusted counts per integration period (IP),  $t_{IP}$  is the duration of an integration period in seconds (0.031032 seconds), and  $S$  is the sensitivity coefficient for this mass. Section 3.2 contains explicit examples that show how to derive the adjusted counts from the measured values.

The IDL routine *inms\_ram\_coefficient.pro* takes mass, speed, and ram angle as inputs and produces the ram coefficient. Chapter 9 of the IDL Analysis Guide, found in the Extras directory on the INMS PDS site, describes an IDL routine that deconvolves the INMS mass spectra to produce a density for each molecule. Magee *et al.* 2009 and Cui *et al.* 2009 also describe deconvolution for minor species. This technique also can increase the accuracy of the major species, but requires attention to the uniqueness of the solution and diligence in understanding the results with respect to the intricacies of the INMS instrument.

In flight, the INMS is less sensitive than during ground testing by a factor of three. The INMS team is quantifying the uncertainty on the factor of three and the calibration papers will be published in 2012. The first published results on Titan neutral densities were uniformly low by a factor of three. Later papers will include this factor of three and will thus be more accurate. Also, future calibration files may include the factor of three. Practically, users must inspect each paper for whether this factor has been included and must read the ReadMe file for each release of INMS data on the PDS to determine whether the calibration file includes the factor-of-three correction.

### 2.2.5 Available auxiliary data

The L1A file contains all the observation-specific data required for analyzing the INMS measurements. The table, below, contains most of the variables used during INMS analysis.

[Type text]

Appendix 6.1 contains a complete list of L1A variables. The routine *inms\_auxiliary\_value.pro* calculates several parameters including latitude, longitude, ram angle, and speed.

L1A variable	Description	Uses
<i>c1counter</i>	High-sensitivity counter	Count rates for low densities
<i>c2counter</i>	Low-sensitivity counter	Count rates when density is high
<i>mass_per_charge</i>	Mass of the measured species	Identifies the molecular mass in AMU
<i>sc_vel_t_scx</i> <i>sc_vel_t_scy</i> <i>sc_vel_t_scz</i>	xyz components of spacecraft velocity relative to target (km/s)	Provides ram velocity and ram angle for calculating the ram-enhancement factor
<i>time_ca</i>	Time in milliseconds from closest approach	
<i>alt_t</i>	Altitude from surface of the target	Height in the atmosphere
<i>source</i>	INMS mode	This users' guide describes analysis of data measured while in the CSN mode
<i>sc_pos_t_x</i> <i>sc_pos_t_y</i> <i>sc_pos_t_z</i>	Position of Cassini in the xyz reference frame of the target body	Latitude and longitude derived from these parameters
<i>coadd_cnt</i>	Number of measurements binned together on board	Most Titan data have <i>coadd_cnt=1</i> , but must check for each data set.

### 2.3 Overview of error calculations

Each INMS measurement is a count of the particles or molecules measured for a given mass during the integration period. Error analyses begin with Poisson counting statistics, which relate a particular count rate to the probability that the count rate accurately represents the measured quantity. The standard deviation for the measured number of counts is the square root of the number of counts. For example, if there are 10 counts measured, then the statistical uncertainty is 3.2, 1 sigma. If counts from several integration periods (IPs) are summed together, then the statistical uncertainty in the new, total count is the square root of the totaled counts. The average count rate per IP is the total count divided by the number of IPs and the uncertainty in the average count rate per IP is the square root of the total count divided by the number of IPs. Bevington (see the reference in Section 5) contains a full description of Poisson statistics.

When summing or binning data, the square root of the total counts only represents the statistical uncertainty, which may be much smaller than other uncertainties. For example, if data from one Titan pass are added to data from another Titan pass, the statistical uncertainty based on the total number of counts will be a smaller percentage of the total counts. However, if the Titan passes had different parameters such as different latitude, altitude, or local sun time, then those differences may be larger than indicated by the statistical error and the combined error is more than the square root of the total counts.

[Type text]

This statistical uncertainty only applies to the measured number of counts. In converting the counts to density, or in sorting out the cracking pattern to determine the fraction of counts in a particular mass channel that belong to a particular parent molecule, there are additional uncertainties, including the uncertainty in the sensitivity calibration, in the cracking ratios, and in the uniqueness of the mass de-convolution.

### 3 Additional example analyses without IDL

This section describes how to reproduce two figures in the Titan-neutral analysis paper, Magee *et al.* 2009. The first figure is a mass spectrum for Titan flyby number 32, T32, and the second figure is the densities vs. altitude for the major species, N<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub> during the same flyby. The same procedures used to produce these figures can be used for all the Titan flybys. All the data required for analyzing the INMS data are on the PDS site. Most of the data, including counts, instrument settings, spacecraft position and attitude, and timing are in the L1A data file. The only other necessary data are the calibration file and the housekeeping data file (see Section 2.1.2).

#### 3.1 Mass spectrum

Magee *et al.* 2009 describes an approach to preparing raw INMS data for composition analysis. Each of the steps, listed in Figure 1 of the document, are described and justified, in detail. Here, this users' guide applies results of that analysis to the T32 flyby and reproduces the mass spectrum shown in Figure 15 of Magee *et al.* 2009. Many of the steps are similar in Cui *et al.* 2009, however details such as constants may be different. In the text, below, there are a few descriptions of the differences between these two referenced papers.

##### *Correction for dead time*

To correct the high-sensitivity counter, C1COUNTS, for dead time, use the following equation:

$$C_m = C_t \times e^{(-C_t \times t_d)} \quad (1) \text{ (from Magee } et al. \text{ 2009, Eq 3)}$$

Where  $C_m$  is the measured count rate,  $C_t$  is the true count rate (per second), and  $t_d=32.6$  ns is the dead time. This correction is relevant between  $10^4$  and  $4 \times 10^4$  measured counts. Below this, the correction is insignificant; above this level, the correction is more complicated and the low-sensitivity counter, C2COUNTS, should be used. At  $4 \times 10^4$  counts, the difference between  $C_t$  and  $C_m$  is 4.5%. Cui *et al.* 2009 uses the same dead time but a higher cutoff limit of  $10^5$  counts.

Since  $C_m$  is the known quantity and  $C_t$  is the desired quantity, we must have a way to convert  $C_m$  to  $C_t$ . Unfortunately, Eq. 1 does not have  $C_t$  as a function of  $C_m$ . To convert the measured counts to true counts, you can build a table of values and then interpolate. A

[Type text]

simpler process, accurate to 0.2% at  $4 \times 10^4$  counts, is to substitute  $C_m$  for  $C_t$  in the exponent. We then have  $C_t = C_m \times e^{(C_m \times td)}$ , which is a convenient form for calculations.

*Saturation: using the low-sensitivity counter, C2COUNTS*

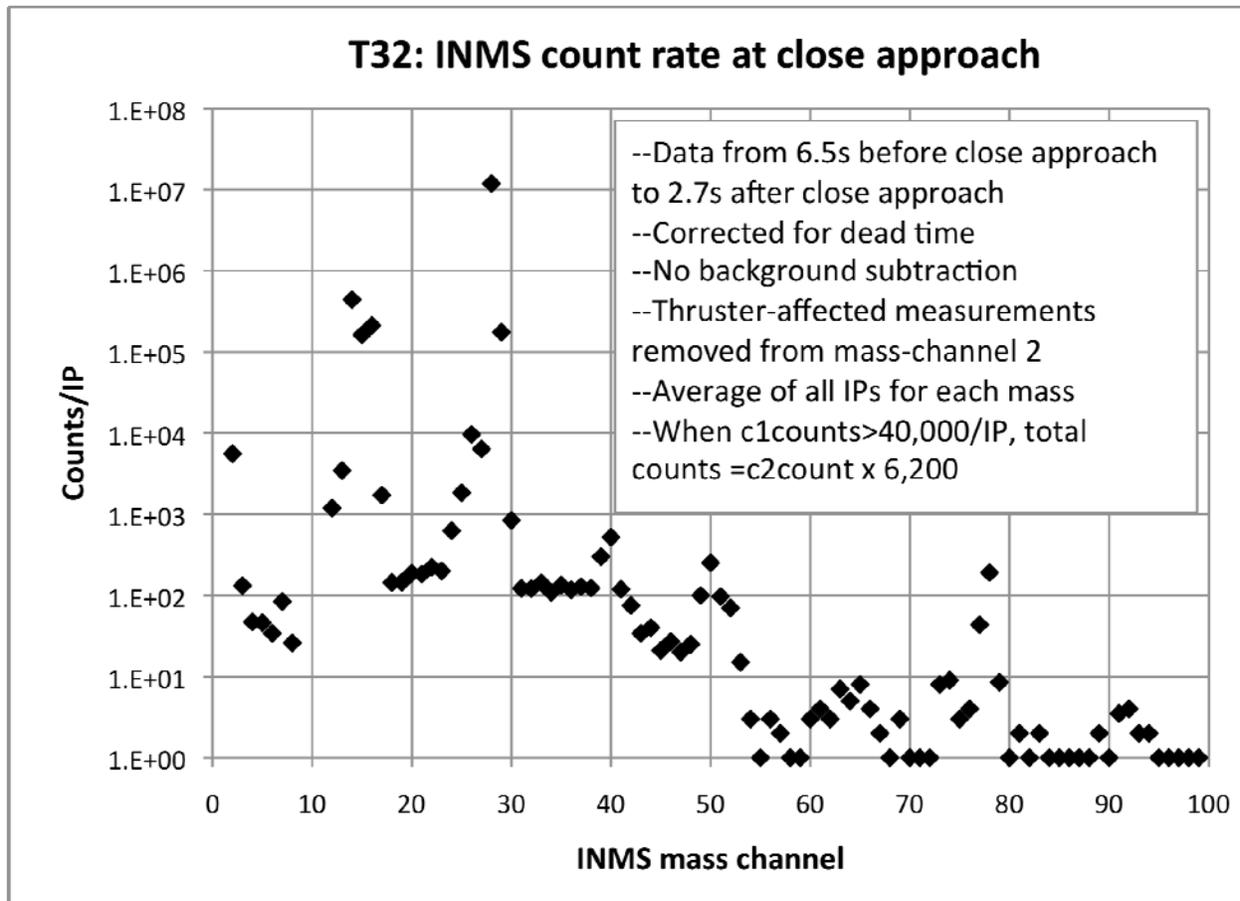
At count rates faster than  $4 \times 10^4$ /IP, *C1COUNTS* cannot be adequately corrected for dead time and other effects. The direct approach is to use the low-sensitivity counter and convert *C2COUNTS* to the true count rate for the low-sensitivity detector using the equation  $C1COUNTS = 6,200 \times C2COUNTS$ . The conversion factor, 6,200, is from Magee *et al.* 2009. Cui *et al.* 2009 uses a conversion factor that depends on the mass channel and varies between 4,000 and 5,750.

A difficult period is when the high-sensitivity detector is only slightly saturated and the count rate on the low-sensitivity detector is low, between about 6 counts and 12 counts per IP. In this regime, the high-sensitivity counter is affected by saturation and the low-sensitivity count rate is so low that statistical uncertainty is high. A solution, described in Magee *et al.* 2009, is to use cracking products to better estimate the true count rate. That technique for increasing precision is not used in this users' guide but can be found in the referenced documents. For this example, we use the direct approach: a upper limit of  $4 \times 10^4$  counts/IP for the high-sensitivity detector and the conversion factor of 6,200 for the low-sensitivity detector, even though there is some scatter during the transition.

When the high-sensitivity detector is fully saturated, its count rate drops to zero. Programs designed to determine when to use the low-sensitivity detector must include logic to select the low-sensitivity detector even though the high-sensitivity detector count rate has fallen due to extreme saturation. The logic used in the analysis for the plots, below, is to use the low-sensitivity counter ( $6,200 \times C2COUNTS$ ) when either the low-sensitivity count rate (*C1COUNTS*) is above the threshold of  $4 \times 10^4$  counts/IP or when *C2COUNTS* is above 30 counts/IP.

*Correction for thruster contamination: H<sub>2</sub>*

During deep penetrations into Titan's atmosphere, Cassini uses thrusters to maintain attitude. The only significant consequence with regard to INMS data is that the molecular hydrogen byproduct is measured in mass channel 2. When INMS measurement of mass channel 2 coincides with a thruster firing, the count rate is anomalously high. By plotting the count rate in mass channel 2, the anonymously high count rates can be identified by inspection and then removed from the data set. Even though this method depends on subjective judgment, it is usually sufficient. Both Magee *et al.* 2009 and Cui *et al.* 2009 contain additional information on this process.



**Figure 8.** This MS Excel plot shows the mass spectrum for Titan flyby T32 with all corrections applied except for high-pressure background subtraction. Near close approach, the observations alternated between two mass tables, and the data for this figure consists of 136 individual measurements provided by the single passes through each mass table that contained the time of closest approach. For each mass with multiple measurements, the measurements were averaged. There were three mass-channel 2 measurements that were removed due to thruster contamination; these measurements were over 20,000 counts, almost four times the other mass-channel 2 measurements that were less than 6,000 counts.

The counts in the high-sensitivity counter, *C1COUNTS*, for masses 14, 15, 16, and 29 were each more than 40,000, indicating that the high-sensitivity counter was inaccurate. For these masses, the adjusted count rates are  $C2COUNTS \times 6,200$ . Although mass 28 had a value of zero for the high-sensitivity detector, the low-sensitivity counter, *C2COUNTS*, was more than 30, so mass 28 also used  $C2COUNTS \times 6,200$  for the adjusted count rate. None of the *C1COUNTS* values were between  $10^4$  and  $4 \times 10^4$ , so the adjustments for dead time did not affect the results. This figure is similar to Fig. 15 in Magee et al. 2009. The only additional correction required is to subtract the high-pressure background, which mostly affects the minor species.

*Correcting for high-pressure effects*

Deep in Titan's atmosphere, N<sub>2</sub> is so dense that it infuses the INMS detector and causes scattering that produces an additional background component. The following equations, derived empirically (Magee *et al.* 2009, Section 2.3), quantify the background for each mass channel when the saturation-adjusted count rate for mass channel 28 is >5x10<sup>6</sup> counts/IP. To remove the background, subtract the calculated background for each mass.

$$B_{m \leq 8} = H_1$$

$$B_{m \geq 12} = H_2 \times \exp \left[ -\frac{((m - G_c)/G_w)^2}{2} \right] + H_3$$

$$H_x = e^{(\ln(C1(28))) \times S_x + I_x}$$

Coefficients
S(H <sub>1</sub> ): 1.87 ± 0.04
I(H <sub>1</sub> ): -26.8 ± 0.60
S(H <sub>2</sub> ): 1.75 ± 0.03
I(H <sub>2</sub> ): -23.3 ± 0.41
G <sub>c</sub> : 24.8 ± 1.14
G <sub>w</sub> : 8.38 ± 1.77
S(H <sub>3</sub> ): 2.16 ± 0.09
I(H <sub>3</sub> ): -35.7 ± 1.5

Where  $B_m$  is the background in counts/IP for mass  $m$ , and C1(28) is the saturation-adjusted count rate for mass channel 28. Cui *et al.* 2009 uses a similar approach with slightly different results.

*Correction for wall adsorption*

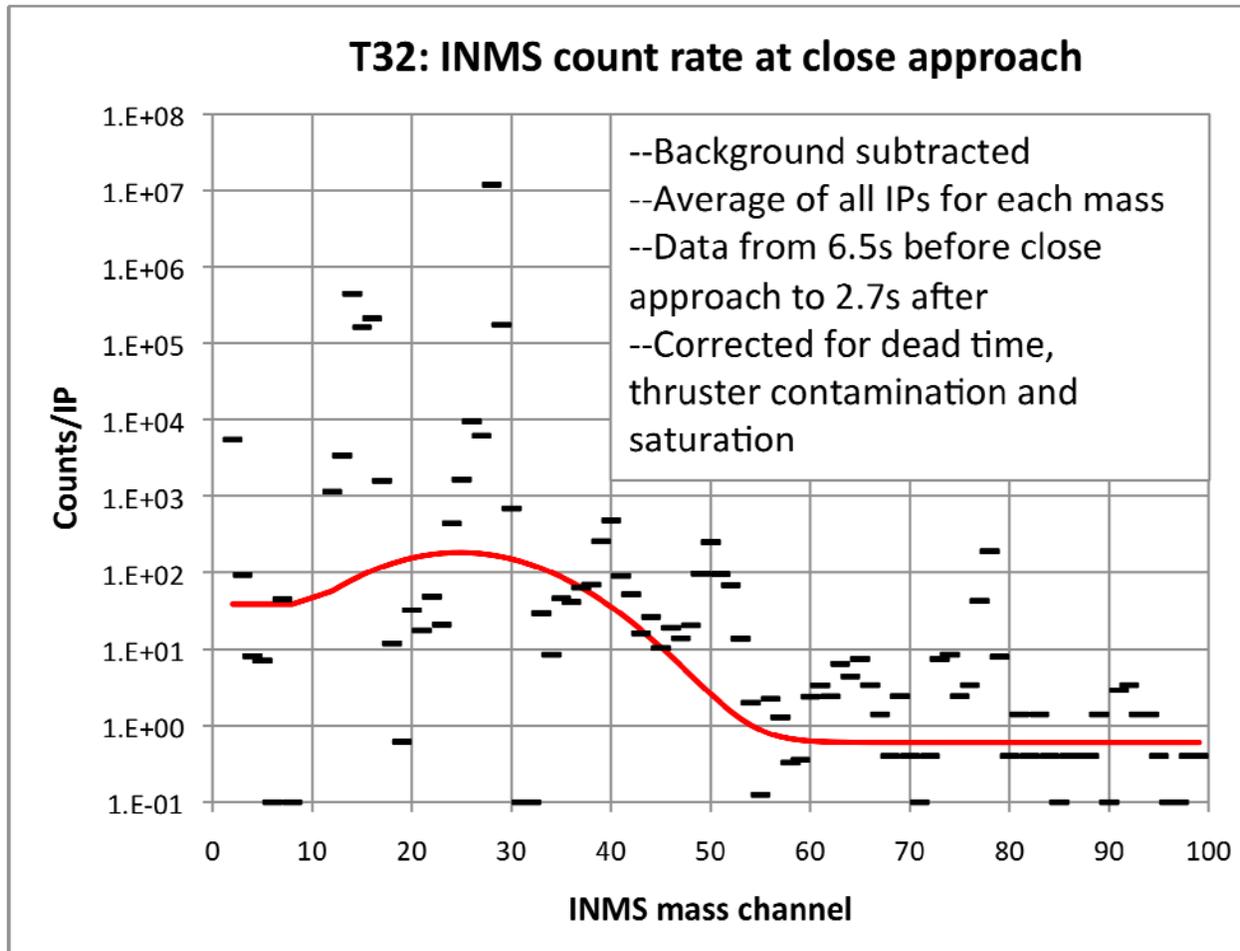
As described in Section 1.3.5, molecules may adsorb onto the walls of the antechamber and transfer tube, and then they release later, potentially reducing the initial count rate and increasing the later count rate. Both Magee *et al.* 2009 and Cui *et al.* 2009 derive corrections for measurements of molecules that interact with the walls. Since these corrections are complex, uncertain because they are empirically derived based on limited data, and are shown by Cui to be negligible for the major species, there is no further description in this users' guide. Users of INMS data should be aware of this effect and should study Magee and Cui if their analyses require the highest-possible accuracy for minor species that may be affected by wall interactions.

*Final mass spectrum*

The figure below shows the high-pressure background and mass spectrum for T32 at close approach. The mass spectrum includes corrections to mass-channel 28 for dead time and for saturation, and the high-pressure background has been subtracted. The high-mass tail of the background is lower than in Figure 22 of Magee *et al.* 2009 because this calculation

[Type text]

uses the general equation for the background described above, and the paper used a background value calculated specifically for these data. It also appears that the time span used in Magee *et al.* spanned an additional 10 seconds of data.



**Figure 9.** A mass spectrum of T32, showing the correction for high-pressure background in red.

### 3.2 Densities and altitude dependence of major species

The corrections in Section 3.1 also apply to calculating the time-dependent densities of major species. The two primary differences are converting the counts to densities and determining the time dependence of the corrections in Section 3.1. Here, we derive the densities for the Titan flyby T32 for the major species, which are H<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>.

#### *Identifying the data files*

There are two quick ways to identify the files containing the data at close approach. Any list of Titan passes (e.g., an appendix of this guide) provides the time of close approach. For T32, close approach is year 2007, day 164, at 17:46:11. On deep-atmosphere passes, Cassini spends 5-6 minutes below 1,500 km, so all the important INMS data are within 10 minutes of close approach. Browse plots such as the figure below for T32 also show the time of close approach, and from the browse plot, it is clear that the Titan pass occurs

[Type text]



N <sub>2</sub>	6.288 x 10 <sup>-4</sup>	51.9	9.88 x 10 <sup>3</sup>
----------------	--------------------------	------	------------------------

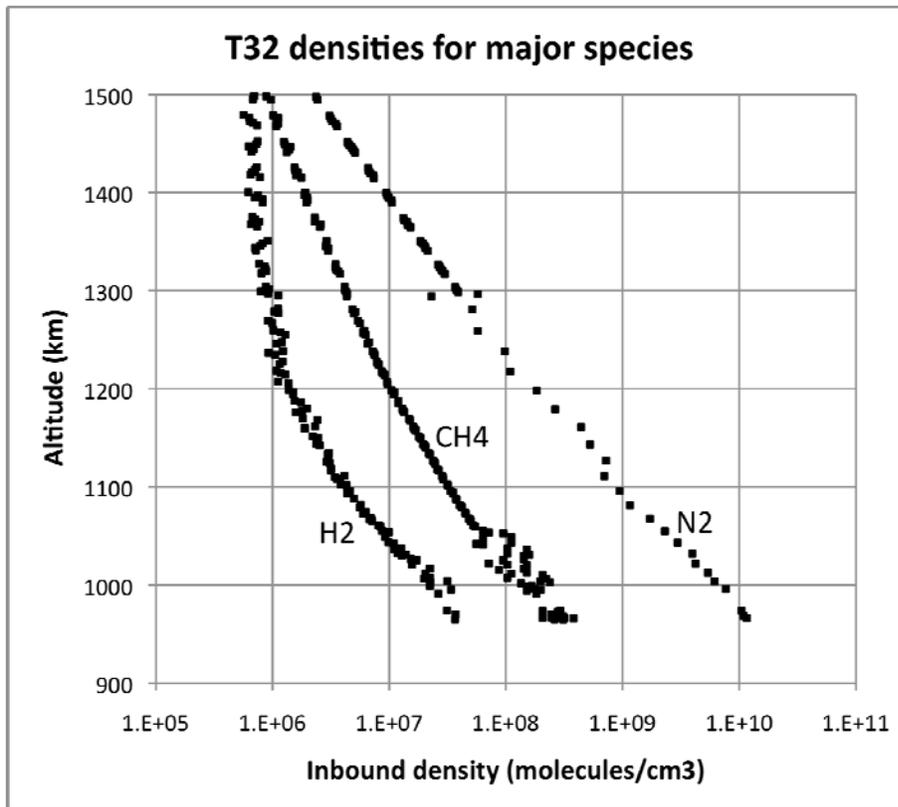
Multiplying the combined factor by the adjusted counts per IP provides the data in the figure, below, which shows the inbound densities for the major species during T32. As described above, the steps to create this plot are

1. Import the data from 200716417\_L1A\_05.csv into the analysis software (IDL, Excel, Matlab, etc.). The INMS PDS users' guide describes how to retrieve these data.
2. Delete columns with data that will not be used in the analysis (this is a convenience)
3. Delete the outbound data: all data with *time\_ca*>0
4. Delete all data from above 1,500 km: all data with *alt\_t*>1500
5. Sort the data by mass
6. Delete mass 2 measurements when contaminated by thruster firings
7. Delete all masses other than the major species, which are masses 2, 16, and 28
8. Convert to total counts by adjusting for dead time and then using the low-sensitivity counter (*C2COUNTS*) when the low-sensitivity channel becomes unreliable (see Section 3.1)
9. Calculate the ram enhancement based on velocity (see Section 3.1)
10. Convert from counts to densities using the values in the table, above.

Variations of these steps also produce plots of count rates vs. time such as those in Figure 10 of Magee *et al.* 2009.

There are several differences between the plot, below, and Figure 22 in Magee *et al.* 2009. The published plot contains many Titan passes but this plot has only T32 data, and it is not possible to determine which data in the published plot are the T32 pass. The C1/C2 factor used in this plot is 5,800, which is the value shown for T32 in Figure 9 of Magee *et al.* 2009. This is slightly lower than the average value of 6,200, but the transition from C1 to C2-based counts is smoother when using 5,800. After transitioning to the C2 counter for CH<sub>4</sub>, the data are noisier than in the published plot. The published plot uses adjustments based on cracking products to smooth the transition between C1 counts and C2-based counts. There are several H<sub>2</sub> densities that are higher than nearby measurements. These high measurements are likely contaminated by thruster maneuvers and should have been removed when the other contaminated mass-2 measurements were deleted. Neither the published plot nor the plot, below, contain the factor-of-three correction.

[Type text]



**Figure 11.** Example plot using spreadsheet analysis of T32.

#### 4 Cautions for using Titan neutral data

- **Saturation** - Counts from the high-sensitivity detector, the *C1COUNTS*, are affected by dead time for count rates above  $2 \times 10^4$  counts/IP. Above  $4 \times 10^4$  counts/IP, saturation affects the high-sensitivity detector and researchers should use cracking products or the low-sensitivity counter (*C2COUNTS*) to determine the correct count rate. See Section 3.1
- **Factor of three** - The flight detector is less sensitive than expected by a factor of three. Densities provided in early papers are low by a factor of three. See section 2.2.4.
- **Wall effects** - Some species interact with the interior walls of INMS, particularly in the antechamber and the transfer tube. This prevents measurement of reactive species such as N and OH, and it distorts the instrument response to other species such as  $\text{NH}_3$  due to sticking that slows the speed that the species travels through the antechamber and transfer tube. If a mass channel's outbound count rates are much higher than the inbound count rates, it is likely that a molecule is adhering to the walls and distorting the signal. A high, extended tail, where the mass channel has counts above background when Cassini has left Titan's atmosphere, is a clear indicator of wall interactions.

- **Effects of high pressure** - The highest densities at Titan increase the INMS background for many mass channels. Although this background has a negligible effect on the count rates for the major species, determination of the minor-species densities are affected by this high-pressure background, which is quantified in Section 3.1.
- **Incorrect summing of data to reduce statistical noise** - Although Poisson counting statistics determine the statistical uncertainty, there are other sources of uncertainty, particularly when adding data acquired during separate Titan passes. Section 2.3 contains additional information.

## 5 Contacts and additional information

Please send comments or questions on this document to

Mark Perry

[mark.perry@jhuapl.edu](mailto:mark.perry@jhuapl.edu)

For additional, detailed information, please see the documentation listed under the following topics:

- The INMS instrument and science objectives:
  - The INMS instrument paper,
    - Waite *et al.* 2004, The Cassini Ion and Neutral Mass Spectrometer (INMS) investigation, *Space Sci. Rev.* **114**, 113.
  - The INMS flight calibration paper
    - In preparation
  - Information and analysis on wall interactions
    - Teolis, *et al.* 2010, Detection and measurement of ice grains and gas distribution in the Enceladus plume by Cassini's Ion Neutral Mass Spectrometer, *J. of Geo. Res.* **115**, A09222.
  - Documentation at the INMS PDS site, particularly the INMS software interface specification (SIS) provided information on the INMS data and data sets
    - The SIS, labeled VOLSIS is archived in several formats (PDF, MSword, etc.) at [http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS\\_3XXX/DOCUMENT/VOLSIS/VOLSIS](http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS_3XXX/DOCUMENT/VOLSIS/VOLSIS)
    - The instrument description document, CO\_INMS\_INST.CAT found at [http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS\\_3XXX/CATALOG](http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS_3XXX/CATALOG)
- Titan neutral analyses:
  - Magee *et al.* 2009, INMS-derived composition of Titan's upper atmosphere: analysis methods and model comparison. *Planetary and Space Science* **57**, 1895-1916.
  - Cui *et al.* 2009, Analysis of Titan's neutral upper atmosphere from Cassini Ion Neutral Mass Spectrometer measurements. *Icarus* **200** (2), 581-615.
  - Mandt *et al.* 2009. Isotopic evolution of the major constituents of Titan's atmosphere based on Cassini data. *Planetary and Space Science* **57** (14-15), 1917-1930
- INMS IDL routines
  - IDL users' guide, found on the PDS site as part of the IDL files in the Extras directory. The link directly to the file is [http://ppi.pds.nasa.gov/ditdos/download?id=pds://PPI/COINMS\\_3XXX/EXTRAS/SOFTWARE/AnalysisGuide.pdf](http://ppi.pds.nasa.gov/ditdos/download?id=pds://PPI/COINMS_3XXX/EXTRAS/SOFTWARE/AnalysisGuide.pdf)
- General error analysis
  - Bevington, "Data reduction and error analysis for the physical sciences," any edition.
- The Cassini-Huygens mission:
  - The Cassini site, at <http://saturn.jpl.nasa.gov/index.cfm>, contains information on the mission, the spacecraft bus, the instruments, the plan, the team members, Saturn, Saturn's moons and rings, and the latest research.
- The software interface specification (SIS), VOLSIS, for INMS data

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[http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS\\_3XXX/DOCUMENT](http://ppi.pds.nasa.gov/search/view/?f=yes&id=pds://PPI/COINMS_3XXX/DOCUMENT)

## 6 Appendices

### 6.1 Contents of INMS archived data files (L1A format)

Part 1

	name	where from	store in	description	type	units	range	format
ip info	ack	ISCLKTIME	SCI	spacecraft clock time	string			C24
	utime	Calc	derived	time of measurement expressed in msec since midnight UTC	int	ms	$0 \leq x \leq 86400000$	I8
	target	Calc	SCAN	name of target body	string		<blank> Saturn titan, ...	C26
	time_ca	Other Kernels	SCAN	time since closest approach	int	ms	$bd \leq 86400000$	I8
	targ_pos_x	Other Kernels	SCAN	position of the target body in the IAU Saturn reference frame	real	km	$bd \leq 10^7$	F9.0
	targ_pos_y	Other Kernels	SCAN	position of the target body in the IAU Saturn reference frame	real	km	$bd \leq 10^7$	F9.0
	targ_pos_z	Other Kernels	SCAN	position of the target body in the IAU Saturn reference frame	real	km	$bd \leq 10^7$	F9.0
scan info	source	OTS	SCAN	ion source used for this measurement	string		cen osl canb oant	C4
	data_reliability	calc		Value is non-zero if there is the possibility of data corruption due to instrument configuration transitions	int		$x \geq 0$	I4
	table_set_id	OTS	SCAN	table set ID number	string			C8
	coadd_cnt	nDataSum	SCAN	specifies the number of IPEs added together. A value of 1 indicates no coadding	int		$1 \leq x \leq 255$	I8
	osp_fil_1_status	FillOn Fields	SCI	Filament 1 status	string		off low high	C6
	oss_fil_2_status	FillOn Fields	SCI	Filament 2 status				
	csp_fil_3_status	FillOn Fields	SCI	Filament 3 status				
	css_fil_4_status	FillOn Fields	SCI	Filament 4 status				
	seq_table	nSeqTable	SCI	sequence table number	int		$1 \leq x \leq 4$	I2
	cyc_num	nCycleIndex	SCI	The cycle index for this sequence	int		$1 \leq x \leq 31$	I2
	cyc_table	nCycleNum	SCI	cycle table number	int		$1 \leq x \leq 84$	I2
	scan_num	nScanIndex	SCI	scan number	int		$1 \leq x \leq 31$	I2
	trap_table	OTS	SCAN	trap table number	int		$1 \leq x \leq 31$	I2
	sw_table	OTS	SCAN	switching table number	int		$1 \leq x \leq 31$	I2
	mass_table	OTS	SCAN	mass table number	int		$1 \leq x \leq 98$	I2
	focus_table	OTS	SCAN	focus table number	int		$1 \leq x \leq 31$	I2
	da_table	OTS	SCAN	D/A table number	int		$1 \leq x \leq 16$	I2
velocity_comp	OTS	SCAN	compensation velocity used in on-board computation of lens and deflector voltages	real	km s <sup>-1</sup>	$0 \leq x < 50$	F6.3	
ip info	ipnum	IP Numbers	IP	integration period number	int		$1 \leq x \leq 68$	I2
	mass_per_charge	OTS	IP	mass	real	Da/z	$0.125 \leq x \leq 99$	F6.3
	os_lens2	OTS	IP	open source lens 2 voltage	real	V	$bd < 10$	F6.2
	os_lens1	OTS	IP	open source lens 1 voltage	real	V	$bd < 10$	F6.2
	os_lens4	OTS	IP	open source lens 4 voltage	real	V	$bd < 62$	F6.2
	os_lens3	OTS	IP	open source lens 3 voltage	real	V	$bd < 62$	F6.2
	qp_lens2	OTS	IP	quadrupole 2 switching lens voltages	real	V	$bd < 200$	F7.3
	qp_lens1	OTS	IP	quadrupole 1 switching lens voltages	real	V	$bd < 200$	F7.3
	qp_lens4	OTS	IP	quadrupole 4 switching lens voltages	real	V	$bd < 200$	F7.3
	qp_lens3	OTS	IP	quadrupole 3 switching lens voltages	real	V	$bd < 200$	F7.3
	qp_bias	OTS	IP	Quadrupole Bias voltage	real	V	$bd < 200$	F7.3
	ion_def2	OTS	IP	ION Deflector 2 voltage	real	V	$bd < 62$	F6.2
	ion_def1	OTS	IP	ION Deflector 1 voltage	real	V	$bd < 62$	F6.2
	ion_def4	OTS	IP	ION Deflector 4 voltage	real	V	$bd < 62$	F6.2
	ion_def3	OTS	IP	ION Deflector 3 voltage	real	V	$bd < 62$	F6.2
	top_plate	OTS	IP	top plate lens voltage	real	V	$bd < 30$	F6.2

[Type text]

Part 2

	name	where from	store in	description	type	units	range	format
	p_energy	Calc	IP	Particle Energy	real	eV		F7.3
	alt_t	Other Kernels	IP	altitude above the surface of the named target body	real	km	bd ≤ 10 <sup>6</sup>	F8.2
	view_dir_t_x	C-Kernels	IP	components of the unit vector in the direction of the INMS aperture outward normal .	real		bd ≤ 1	F8.6
	view_dir_t_y	C-Kernels	IP					
	view_dir_t_z	C-Kernels	IP					
	sc_pos_t_x	Other Kernels	IP	x component of spacecraft position wrt the named target	real	km	bd ≤ 10 <sup>6</sup>	F8.2
	sc_pos_t_y	Other Kernels	IP	y component of spacecraft position wrt the named target	real	km	bd ≤ 10 <sup>6</sup>	F8.2
	sc_pos_t_z	Other Kernels	IP	z component of spacecraft position wrt the named target	real	km	bd ≤ 10 <sup>6</sup>	F8.2
	sc_vel_t_x	Other Kernels	IP	x component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_t_y	Other Kernels	IP	y component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_t_z	Other Kernels	IP	z component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_t_scx	Other Kernels	IP	spacecraft frame x component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_t_scy	Other Kernels	IP	spacecraft frame y component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_t_scz	Other Kernels	IP	spacecraft frame z component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	lst_t	C-Kernels	IP	local solar time at the sub-spacecraft point on the target body	real	hours	0 ≤ x ≤ 24	F8.3
	sza_t	C-Kernels	IP	solar zenith angle at the sub-spacecraft point on the target body	real	deg	0 ≤ x ≤ 180.	F7.3
	ss_long_t	C-Kernels	IP	longitude of the sub-solar point on the target body on the target body	real	deg	0 ≤ x ≤ 360.	F6.2
	distance_s	Other Kernels	IP	distance between spacecraft and center of Saturn	real	km	bd ≤ 10 <sup>7</sup>	F8.0
	view_dir_s_x	C-Kernels	IP	components of the unit vector in the direction of the INMS aperture outward normal	real		bd ≤ 1	F8.6
	view_dir_s_y	C-Kernels	IP					
	view_dir_s_z	C-Kernels	IP					
	sc_pos_s_x	Other Kernels	IP	x component of spacecraft position	real	km	bd ≤ 10 <sup>7</sup>	F8.0
	sc_pos_s_y	Other Kernels	IP	y component of spacecraft position	real	km	bd ≤ 10 <sup>7</sup>	F8.0
	sc_pos_s_z	Other Kernels	IP	z component of spacecraft position	real	km	bd ≤ 10 <sup>7</sup>	F8.0
	sc_vel_s_x	Other Kernels	IP	x component of spacecraft velocity	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_s_y	Other Kernels	IP	y component of spacecraft velocity	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	sc_vel_s_z	Other Kernels	IP	z component of spacecraft velocity	real	km s <sup>-1</sup>	bd ≤ 100	F7.3
	lst_s	C-Kernels	IP	local solar time at the sub-spacecraft point on Saturn	real	hours	0 ≤ x ≤ 24	F8.3
	sza_s	C-Kernels	IP	solar zenith angle at the sub-spacecraft point on Saturn	real	deg	0 ≤ x ≤ 180.	F7.3
	ss_long_s	C-Kernels	IP	longitude of the sub-solar point on the target body on Saturn	real	deg	0 ≤ x ≤ 360.	F6.2
	sc_att_angle_ra	C-Kernels	IP	right ascension of spacecraft z axis	real	rad	0 ≤ x ≤ 2π	F8.6
	sc_att_angle_dec	C-Kernels	IP	declination of spacecraft z axis	real	rad	-π/2 ≤ x ≤ π/2	F8.6
	sc_att_angle_tw	C-Kernels	IP	rotation of spacecraft about z axis	real	rad	0 ≤ x ≤ 2π	F8.6
	c1counts	C1Counters	SCI	high sensitivity counts	int		0 ≤ x ≤ 10 <sup>6</sup>	I6
	c2counts	C2Counters	SCI	low sensitivity counts	int		0 ≤ x ≤ 10 <sup>6</sup>	I6

[Type text]

## 6.2 Times of Cassini flybys of Titan

These are the dates for each Cassini encounter with Titan. DOY is the day of year. The times are at the minimum altitude, which is given in the last column. Only flybys with minimum altitudes below 1,500 km are listed. The time of each Titan pass is also on the Cassini site, and the site <http://saturn.jpl.nasa.gov/mission/flybys/> contains data on the most-recent flybys. The label and parameters for future flybys may change.

<b>Titan Flyby</b>	<b>Date Year-DOY</b>	<b>Time of closest approach</b>	<b>Minimum altitude (km)</b>
TA	2004-300	15:30:05	1,174
T5	2005-106	19:11:46	1,027
T16	2006-203	0:25:25	950
T17	2006-250	20:16:50	999
T18	2006-266	18:58:48	964
T19	2006-282	17:30:06	984
T21	2006-346	11:41:30	1,004
T23	2007-013	8:38:30	1,000
T25	2007-053	3:12:24	1,000
T26	2007-069	1:49:00	985
T28	2007-100	22:57:59	991
T29	2007-116	21:32:58	981
T30	2007-132	20:09:58	960
T32	2007-164	17:46:11	965
T36	2007-275	4:42:43	973
T37	2007-323	0:47:25	1,000
T39	2007-354	22:57:54	970
T40	2008-005	21:30:19	1,014
T41	2008-053	17:32:07	1,000
T42	2008-085	14:27:47	1,001
T43	2008-133	10:01:57	1,001
T44	2008-149	8:24:32	1,400
T48	2008-340	14:25:45	961
T49	2008-356	12:59:52	970
T50	2009-038	8:50:50	967
T51	2009-086	4:43:36	963
T55	2009-141	21:26:41	966
T56	2009-157	20:00:00	968
T57	2009-173	18:32:34	955
T58	2009-189	17:04:03	966
T59	2009-205	15:34:03	956
T61	2009-237	12:51:37	960
T64	2009-362	0:16:59	955
T65	2010-012	23:10:36	1,073

[Type text]

<b>Titan Flyby</b>	<b>Date Year-DOY</b>	<b>Time of closest approach</b>	<b>Minimum altitude (km)</b>
T-70	2010-172	01:27:44	880
	2010-188	00:22:45	1005
	2011-171	18:32:01	1359
	2012-143	1:10:11	955
	2012-159	0:07:21	959
	2012-206	20:03:08	1012
	2012-270	14:35:39	956
	2012-318	10:22:09	973
	2012-334	8:57:00	1014
	2013-95	21:43:32	1400
	2013-143	17:32:56	970
	2013-191	13:21:48	964
	2013-207	11:56:23	1400
	2013-255	7:43:57	1400
	2013-287	4:56:28	961
	2013-335	0:41:20	1400
	2014-1	21:59:42	1400
	2014-33	19:12:39	1236
	2014-65	16:26:48	1500
	2014-97	13:41:15	963
	2014-233	8:09:10	964
	2014-265	5:23:20	1400
	2014-297	2:40:31	1013
	2014-344	22:26:36	980
	2015-11	19:48:36	970
	2015-43	17:08:05	1200
	2015-271	21:37:14	1036
	2016-32	1:01:26	1400
	2016-47	23:52:04	1018
	2016-95	19:48:00	990
	2016-127	17:00:46	971
	2016-159	14:12:38	975
	2016-207	10:04:40	976
	2017-112	6:20:04	979

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### 6.3 Glossary and acronyms

- *coadd\_cnt*: a variable that indicates the number of measurements that are added together on board Cassini before the data are transmitted to the ground.
- Cracking products: The different masses that can be produced when a neutral molecule is ionized in the INMS ionization chamber.
- CSN: the Closed Source Neutral mode for INMS.
- INMS: Cassini's Ion and Neutral Mass Spectrometer
- L1A files: the data files containing INMS measurements. These files include ancillary data used to analyze INMS data.
- mass spectrum: A plot of count rate vs mass channel, showing the distribution of counts for the selected masses.
- Primary species: Hydrogen, Methane, and Nitrogen, H<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>
- Ram angle: the angle between the INMS boresight and the velocity vector of particles measured by INMS
- Ram enhancement: the additional sensitivity INMS acquires when high-velocity neutrals enter the CSN antechamber.
- SIS: Software Interface Specification, a PDS document that describes data for a particular instrument
- T<sub>n</sub>: the n<sup>th</sup> flyby of Titan