

## **Users' guide for analyzing INMS ion data from Titan's ionosphere**

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## Table of contents

1.....	3
1 Introduction.....	3
1.1 Purpose.....	3
1.2 Overview of this document.....	3
1.3 Overview of the INMS instrument.....	4
1.3.1 Instrument orientation on Cassini.....	4
1.3.2 Operational modes.....	4
1.3.3 Measurement parameters.....	7
1.3.4 Sensitivity of count rate to total energy.....	8
1.3.5 Field of view and cross winds.....	9
1.4 The INMS team.....	10
2 Introduction to analyzing INMS ion data from Titan.....	10
2.1 INMS data.....	10
2.1.1 Locating and downloading INMS data for local processing.....	10
2.1.2 Example overview plots.....	11
2.1.3 Structure of INMS data.....	13
2.1.4 Energy scans.....	14
2.2 INMS analyses.....	15
2.2.1 Downloading IDL routines developed for INMS.....	15
2.2.2 Importing INMS data into IDL and other programs.....	15
2.2.3 Analyzing INMS data using IDL tools.....	16
2.2.4 Details of converting counts to densities.....	19
2.2.5 Available auxiliary data.....	23
2.3 Overview of uncertainty.....	24
3 Additional example analyses without IDL.....	25
3.1 Mass spectrum: density vs. mass.....	27
3.2 Densities and altitude dependence of individual species.....	28
4 Cautions for analyzing Titan ion data.....	30
5 Contacts and additional information.....	30
6 Appendices.....	33
6.1 Contents of INMS archived data files (L1A format).....	33
6.2 Times of Cassini flybys of Titan.....	35
6.3 Glossary and acronyms.....	37

## 1 Introduction

### 1.1 Purpose

The Ion and Neutral Mass Spectrometer (INMS) produces a wealth of data on Titan's ionosphere, 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,
- spacecraft potential, and
- environmental factors, particularly wind.

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 that users can perform their own research using INMS ion data from Titan. There is a separate guide for analyzing INMS data on Titan neutrals.

This guide contains example analyses, including computing the total ion density, a mass spectrum, and the time-dependent density of a single species. These calculations are described in detail and then demonstrated using two different tool sets.

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 ions in Titan's ionosphere. The discussion includes detailed examples that can be replicated. The section includes a description of how to convert INMS counts to ion density. In following these steps, researchers can begin to acquire the knowledge and build the competency required for independent analyses and use of the data. In this document, the terms "ionosphere" and "upper atmosphere" are both used to describe the region measured by INMS, the region that is 1000 – 1500 km from Titan's surface.

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 the ion density mass spectrum and an altitude history of a single species.

Section 4 reiterates several potential analysis problems, each of which was discussed in detail in Section 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 ionosphere and upper atmosphere and their 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.

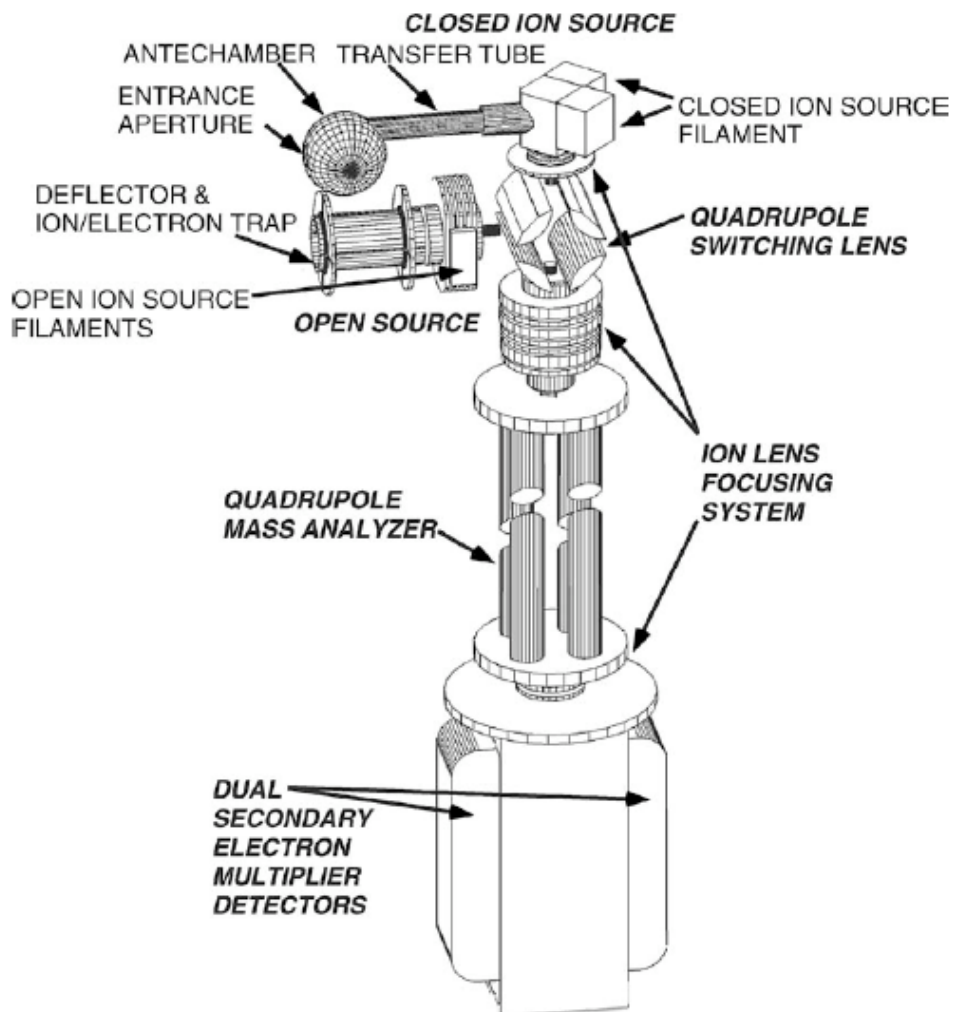
#### **1.3.1 Instrument orientation on Cassini**

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 may still gather useful ion data if the INMS aperture is pointed within five degrees of the ram direction.

#### **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).

The ion analyses described in this guide use data from the OSI mode. 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  $C_6H_6$ .

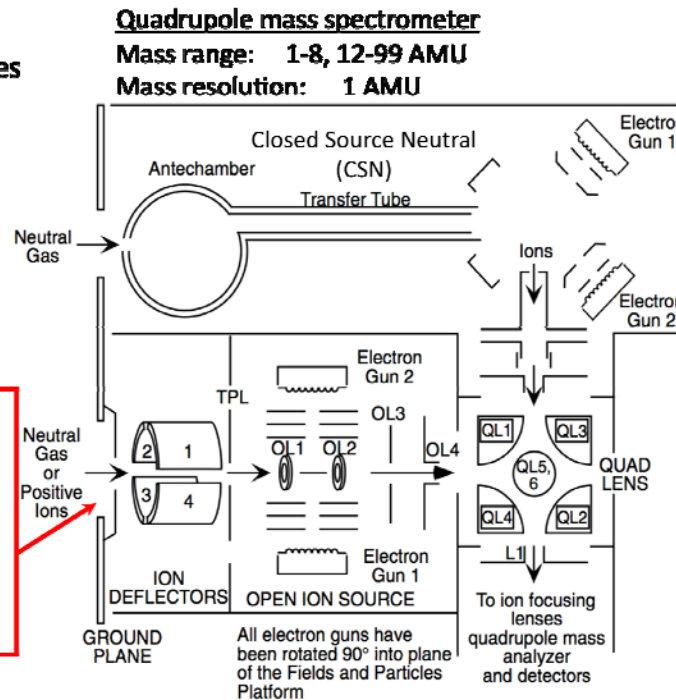


**Figure 1a.** Schematic of INMS showing the major components.

**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**



**Figure 1b.** Diagram of the INMS inlet system. All ion data are measured using the open source. The quad-lens voltages determine the energy of the ions that are transmitted into the quadrupole analyzer (not shown), which then removes all ions except for those with the selected mass-to-charge ratio.

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. Each measurement period is called an integration period or IP, which has a fixed period of 31 milliseconds. During each IP, INMS counts the number of particles with the specified mass. For more information on the CSN mode and on INMS neutrals, see the Users' guide for analyzing INMS data on Titan's neutral atmosphere.

INMS measures ions using the OSI mode, which uses the open source aperture. The field of view (FOV) of the OSI aperture is 3 to 5 degrees, depending on the speed and mass of the ions. To measure the ions, Cassini rotates so that the OSI aperture faces toward the incoming ions. Since the velocity of the ions in Titan's ionosphere is usually 100 to 300 m/s, which is much less than Cassini's velocity through the ionosphere, approximately 6 km/s, the OSI aperture must point in the direction that Cassini is moving. During each IP, INMS measures ions with the requested mass and the preset speed, the velocity compensation parameter, or  $V_{COMP}$ . Both the measured masses and  $V_{COMP}$  are set by ground command before the flyby.  $V_{COMP}$  is the predicted flyby speed and is used to set internal INMS voltages based on the ion energy derived from the mass and by  $V_{COMP}$ . As described in Section 2.2.4, if the actual energy differs from the predicted energy, INMS count rate drops.

For each observation of an ion, the INMS voltages are set to admit particles with the expected energy of the desired ion. These are the switching-lens voltages. The mass analyzer then filters out all ions except those with the desired mass-to-charge ratio, and the INMS detector then records the remaining ions.

**1.3.3 Measurement parameters**

INMS makes a measurement every 34 ms, which includes the duration of the integration period (the IP) of 31 ms plus 3 ms for INMS voltages to settle for the next measurement. Each measurement is the number of detector counts for ions of one mass at one velocity. (Actually, the measurement is for ions of one mass-to-charge ratio. Since the number of doubly-ionized ions in Titan’s ionosphere is negligible, the charge is 1 and the mass-to-charge ratio is equivalent to mass.) A table of masses specifies which mass to measure or count during each IP. This mass table contains 68 entries, which are measured in sequential order during each pass through the mass table, which takes  $68 \times 0.034 = 2.3$  seconds. Often, important masses have several entries in a single mass table so that they are measured more often than once every 68 IPs. During most observations, INMS alternates between two mass tables for the OSI mode, and a complete mass spectrum includes at least one pass through each of the mass tables. The table below shows one of the mass tables used to determine which ions were measured during the T32 encounter. There are separate mass tables for the other instrument modes. INMS may use more than 10 mass tables during a single Titan encounter, but only a few of the tables provide measurements of interest when analyzing ions. Researchers can ignore measurements made when the other tables are used.

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

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

### 1.3.4 Sensitivity of count rate to total energy

For each single measurement—for each IP—INMS measures ions with the designated mass and a specific energy that is defined by the voltage settings. These settings are loaded onto the spacecraft based on the expected energy of the ions to be measured. If the energies of the desired ions are different than expected, then fewer ions pass through the switching lens, reducing the INMS count rate. The INMS team treats this loss in sensitivity as a transmission loss. Practically, there are several factors that cause the energy settings to be different from the energies of the desired ions:

1. The spacecraft potential may be different than the assumed value. Only ions with the correct total energy are admitted, and the spacecraft potential affects that total energy. Although the spacecraft potential is usually within a few tenths of a volt of -0.5 V, it can vary rapidly and can be as large as -2.0 V, which can reduce the count rate by more than three orders of magnitude. Before T41, INMS settings assumed a zero spacecraft potential; afterwards, the energy predictions assumed a -0.5 V potential.
2. The velocity of the spacecraft may be different than assumed. These errors were greater and more-frequent early in the mission, but are relatively low for passes after T40.
3. Usually, the largest contributions to transmission uncertainty are the wind speed and direction. The along-track component of wind speed changes the ion energy, affecting transmission, and the cross-track component drives the ions away from the boresight axis and reduces the number of ions within the OSI field of view (FOV). Detailed comparison of INMS measurements with the Cassini Plasma Spectrometer (CAPS) Ion Beam Spectrometer (IBS) can produce estimates of the along-track component of the winds, but there are no Cassini instruments that provide information on the cross track winds. The winds are thus the largest contribution to uncertainty. The winds are faster at higher altitude, which increases uncertainty at the higher altitudes.
4. There are coefficients in the INMS on-board software that convert the predicted energy to voltage settings. If these are incorrect, then it is similar to an error in the energy. Before T41, these settings differed from the near-optimal values used in later passes.

Section 2.2.4 has more information on the effects of energy errors and the corrections necessary for calculating densities from the measured count rates.



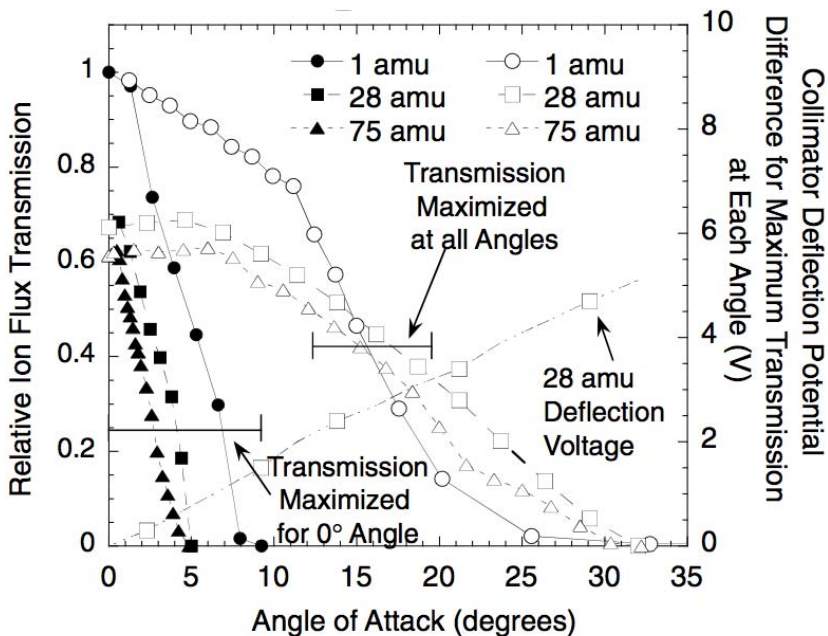
Errors in energy do not combine linearly. For example, a reduction in transmission caused by spacecraft potential that is different from the pre-loaded value can be much greater if ion winds have already pushed the energies away from the desired value.

When analyzing INMS ion data, researchers can adjust the density calibration by accounting for the differences between the predicted and actual values. For errors due to spacecraft velocity and modeling errors (items 2 and 4, above), these corrections have a low uncertainty. When using RPWS data for the spacecraft potential, item 1 also can be well determined. However, correcting for the wind speed and direction is often impossible and is difficult and uncertain, at best. Section 2.2.4 describes some additional issues and approaches, and Mandt *et al.*, 2012, describes these effects in detail.

### 1.3.5 Field of view and cross winds

As seen in Figure 2, the OSI field of view (FOV) varies with the mass or energy of the ion. The velocities of the Titan passes are all close to 6 km/s, so the FOV energy dependence translates to a mass dependence.

Wind velocities in Titan's ionosphere are typically 100 m/s, but they may be 300 m/s based on models and on IBS measurements of along-track winds. A 300 m/s crosswind produces an incident angle of  $0.3/6.0 = 0.05$  radians or 2.8 degrees, which is enough to reduce transmission by 50% for heavier ions. Since the FOV is mass dependent, the transmission attenuation is also mass dependent, with a larger effect on the larger masses. Crosswind effects are independent of the accuracy of the energy settings and always reduce ion transmission and count rate. There is no instrument on Cassini that can measure the crosswind speed, so crosswinds are one of the largest sources of error and cannot be calibrated away.



**Figure 2** The field of view for INMS in the OSI mode for several different masses and for two types of settings. These calculations were all based on the same velocity, 6 km/s, so the different masses represent different energies. The in-flight INMS uses the narrower “Transmission Maximized for 0° Angle” settings. The half-width FOV varies from approximately 5° for the lighter, lower-energy ions to less than 2° for the heaviest ions. From Waite et al., 2004, Figure 22.

#### 1.4 The INMS team

Hunter Waite, at Southwest Research Institute. (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 ion data from Titan

### 2.1 INMS data

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

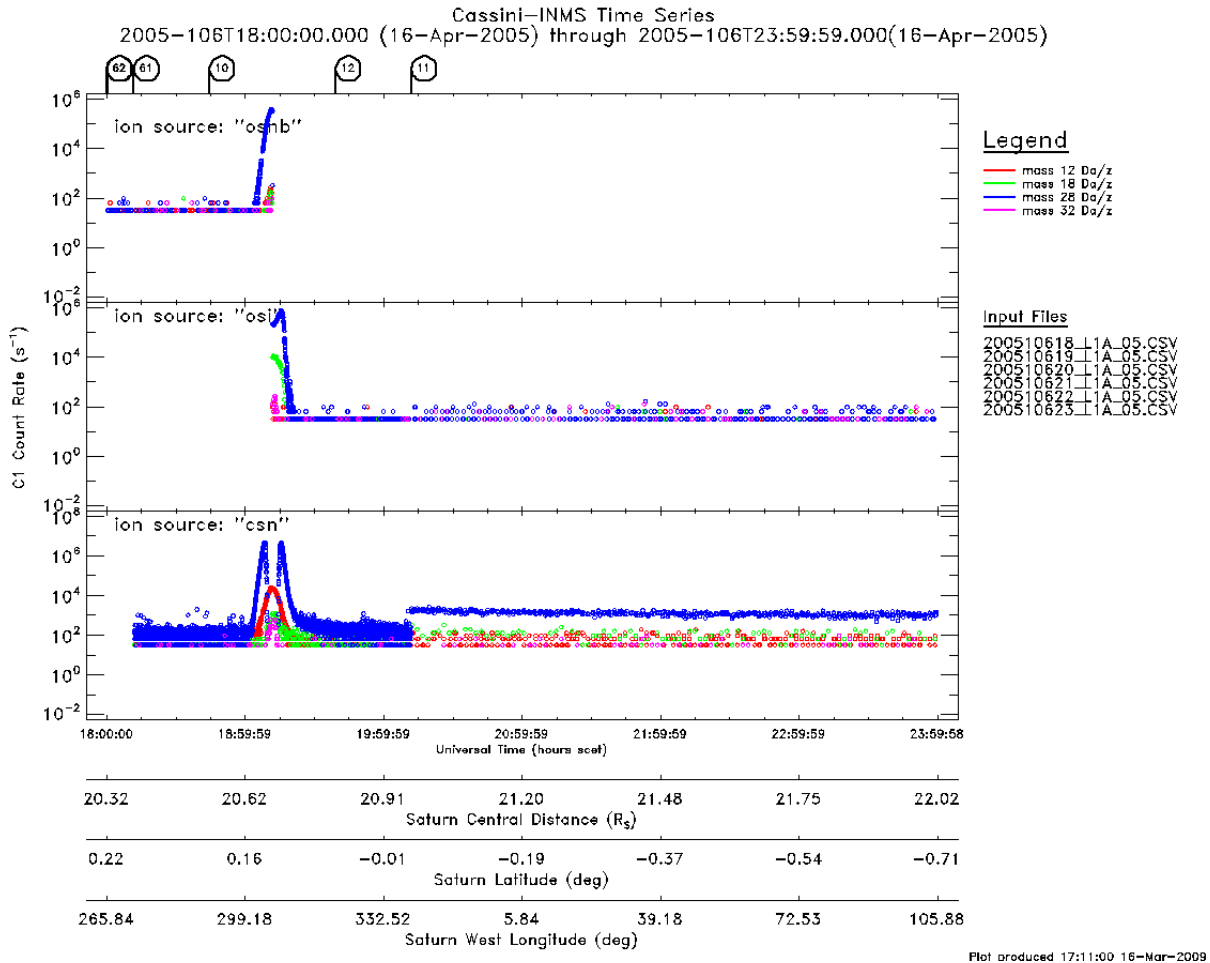
A separate users' guide, *The INMS PDS Users' Guide*, describes how to locate INMS data and how to download data and processing routines.

### 2.1.2 Example overview plots

Examples of the two types of overview plots are shown in Figures 3 and 4. 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.

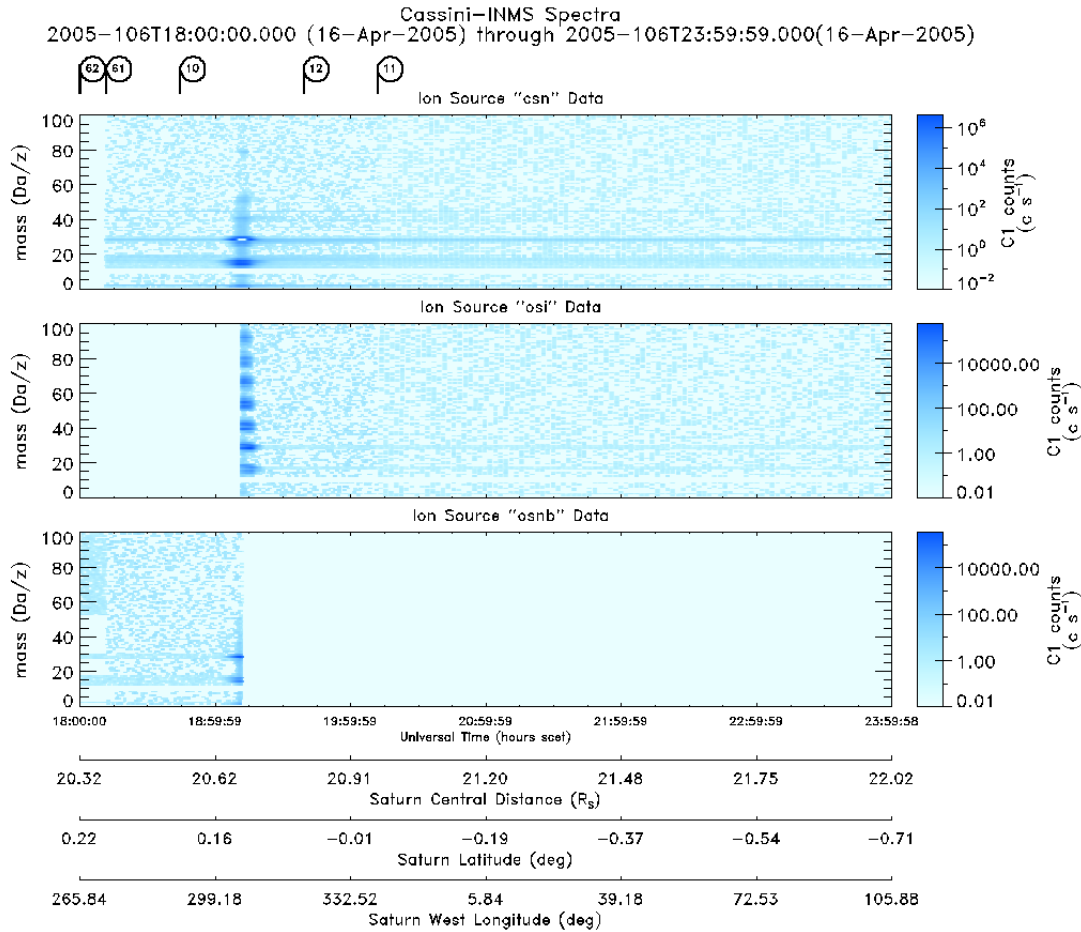
Figure 3 is a line plot and shows several important aspects of Titan data:

- 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 panel of Figure 3) until about 19:07, just before the time of closest approach, and then INMS operation switched to the OSI mode (the middle panel of Figure 3).
- b) The OSI signal shows that the density for the mass-28 ion,  $\text{HCNH}^+$  (blue line), drops at the deepest penetration into Titan atmosphere. Changes in both the ion source and loss contribute to this reduction in density. At this depth in the ionosphere, there are fewer photons available to create the ions that lead to  $\text{HCNH}^+$ , and there also is a higher neutral density that increases  $\text{HCNH}^+$  loss through recombination.
- c) The CSN plot of the neutral density shows an apparent reduction in density at the lowest altitudes. Unlike the ion density, this is an artifact of the INMS. As with most Titan passes,  $\text{N}_2$  saturates (exceeds the maximum possible count rate) 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.
- d) The character of the OSI and CSN signals 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 Cassini encounter with Titan that occurred on Cassini’s fifth orbit of Saturn. This is a copy of the browse plots that are available on the PDS site or through the INMS IDL library. Since the browse plots are intended for analysis, not publication, and since these figures are exact copies of the browse plots, the labels are smaller than desired for a printed version.

This second BROWSE plot, Figure 4, is the mass-spectrum plot which shows all masses, but with less resolution in the count rates. As with Figure 3, each panel corresponds to a different mode of INMS, but the order of the modes is different between the two figures. In both figures, OSI is the middle or center panel.



Plot produced 17:10:51 16-Mar-2009

**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 (RS), Saturn latitude (degrees), and Saturn longitude (degrees west). All four of these units can be plotted with respect to Titan. As with Figure 3, the labels are smaller than desired for a printed version of the plots.

### 2.1.3 Structure of INMS data

The INMS data files are simple lists of comma-separated variables. In INMS nomenclature, this is the “L1A” file and it represents data that are processed to level 1A, which means that these are raw data that are neither calibrated nor adjusted in any other way. 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<sup>5</sup> rows and be greater than 50 MB in size.

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",
```

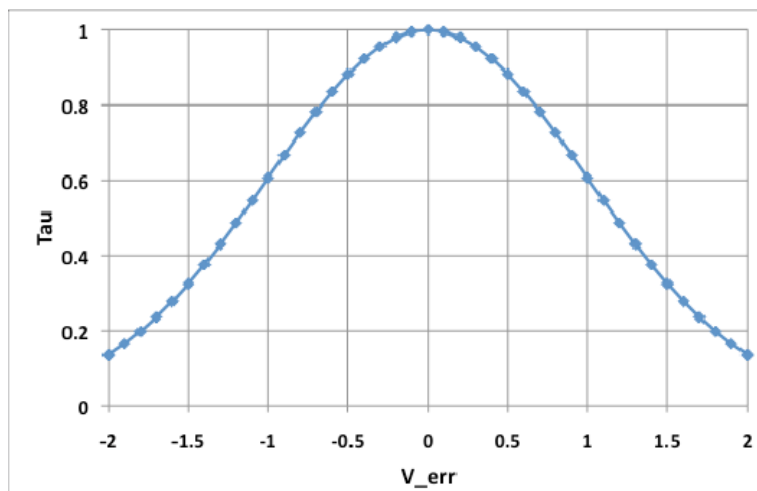
In this example, all the target-related data (target name, time of closest approach, position relative to the target) are blank because there was no target identified for this observation.

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"
```

### 2.1.4 Energy scans

Every pass through the Titan ionosphere includes calibration measurements where some of the INMS voltage settings are varied or scanned through a range of values while measuring the count rate for a particular ion mass. These measurements, labeled “energy scans” because the scanned voltage settings determine the energy of the detected ions, show the sensitivity of INMS count rate to the instrument settings and enable calibration of the ion data. Mandt et al., 2012 describes the calibration process, but that knowledge is not required for most analyses of ion data. These data, which are used by the INMS team for calibration and are incorporated into the calibration coefficients, can be ignored for most analyses of INMS ion data. Each energy scan uses several mass tables.



**Figure 5.** This plot shows a curve that fits the energy-scan data. The X axis represents the deviation of the ion energy—represented by the error in  $V_{QL3}$ —from the optimal setting. If the voltage is more or less than the optimal setting, transmission through the quadruple is reduced by a fraction that increases with larger deviations. This curve represents  $\tau$ , which is described in Section 2.2.4.

## 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 Analysis Guide 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.

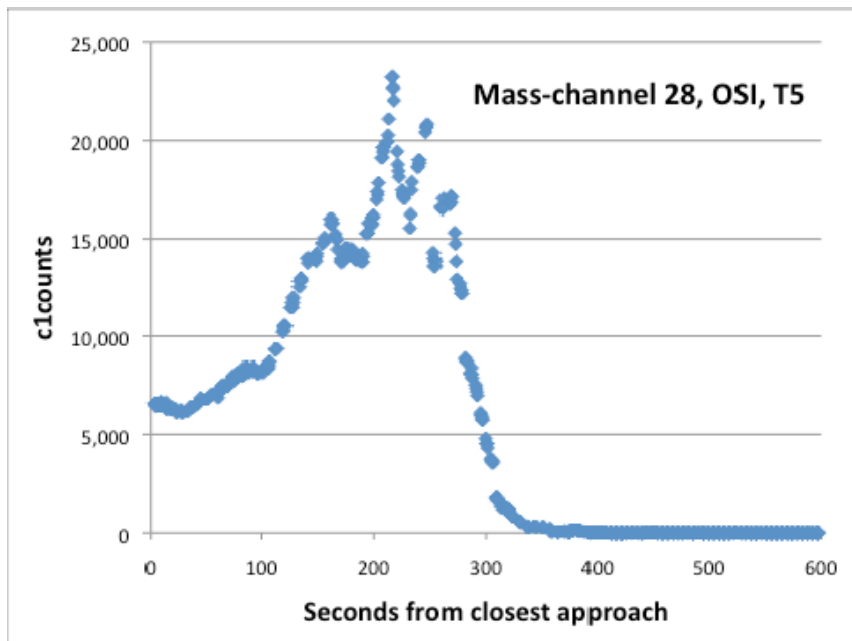
The output of *inms\_get\_data.pro* is a structure variable with the first parameter specifying the variable name (*output\_var*). The output variable name *axData* is common throughout INMS documentation of IDL routines for the name of the structure variable of L1A data. This structure variable has 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, Figure 6, 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 OSI (sort on the “source” column and delete all “csn” “osnb” etc. rows), the file is reduced to 40,000 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

2,700. 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. (There are no MATLAB examples in this guide.)



**Figure 6** Example of INMS ion data plotted using spreadsheet graphics.

### 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, Figures 3 and 4, in Section 2.1.2. Once the data are downloaded, the four commands in italics can be cut and pasted and will produce the browse figures. The only required changes are to replace the file names (they are underlined) with the actual values.

- a) *inms\_get\_data, output\_file, files=['L1A input file1', 'L1A input file2']*

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” represents 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 OSI data, only. The output of this command is Figure 3.
- d) *inms\_plot\_mt\_spectra, axData, /target*  
This creates the mass-spectra time-history plot, Figure 4.

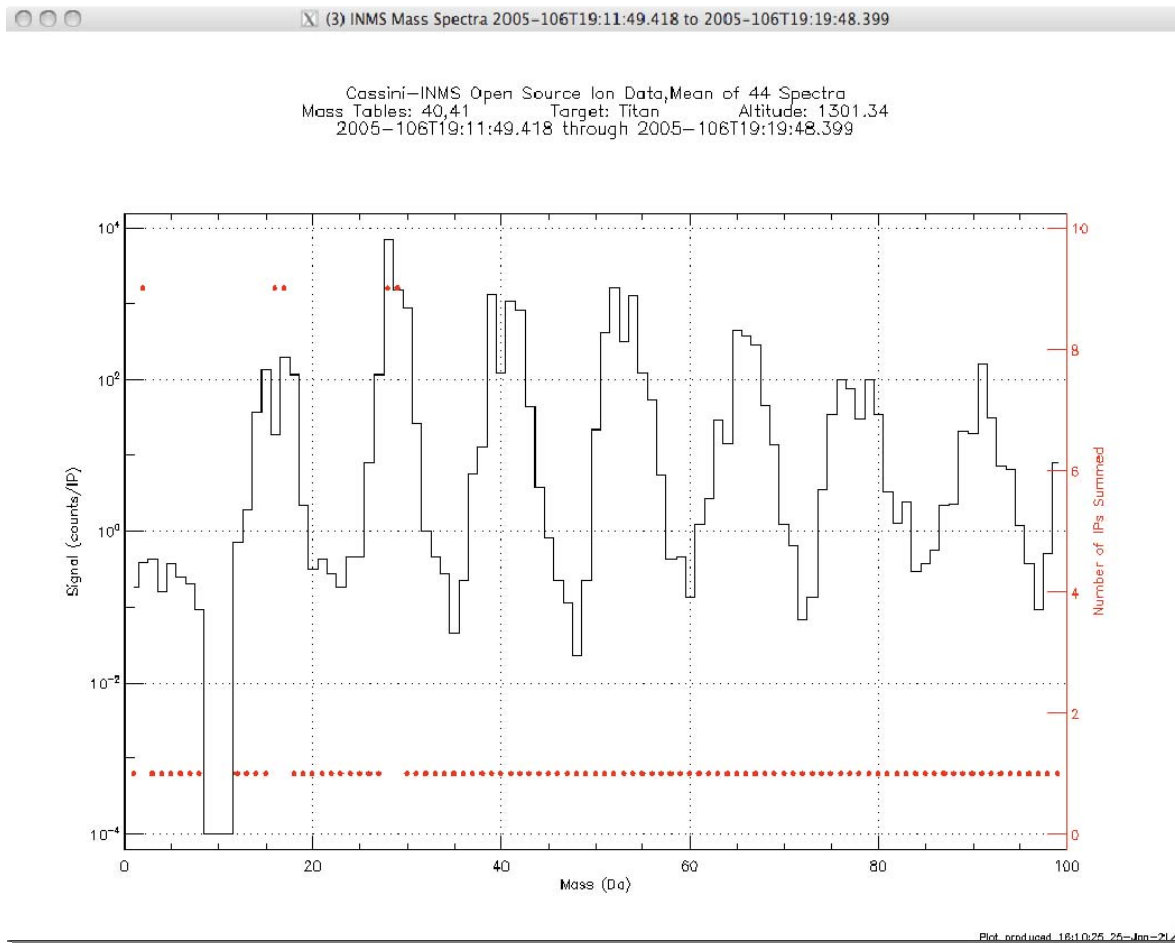
To compute and display a mass spectrum:

- 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 co-add count (*coadd\_cnt*), 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 OSI 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 OSI mode and mass tables used for observations in other modes.
- b) *inms\_get\_spectra, axData, axSpec, source='osi', masstableid=[40, 41], 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 the closest 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 individual measurements) during the selected period. For T5 hour 19, which includes the closest approach, OSI measurements below 2,000 km use mass table IDs 40 and 41, and these same mass tables were used for T32 at the closest approach. (This does not include the mass tables used for the energy scans; see Section 2.1.4.) The structure variable, *axSpec*, contains 29 fields for each spectrum, including UTC time, time relative to the closest 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 the closest 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*.

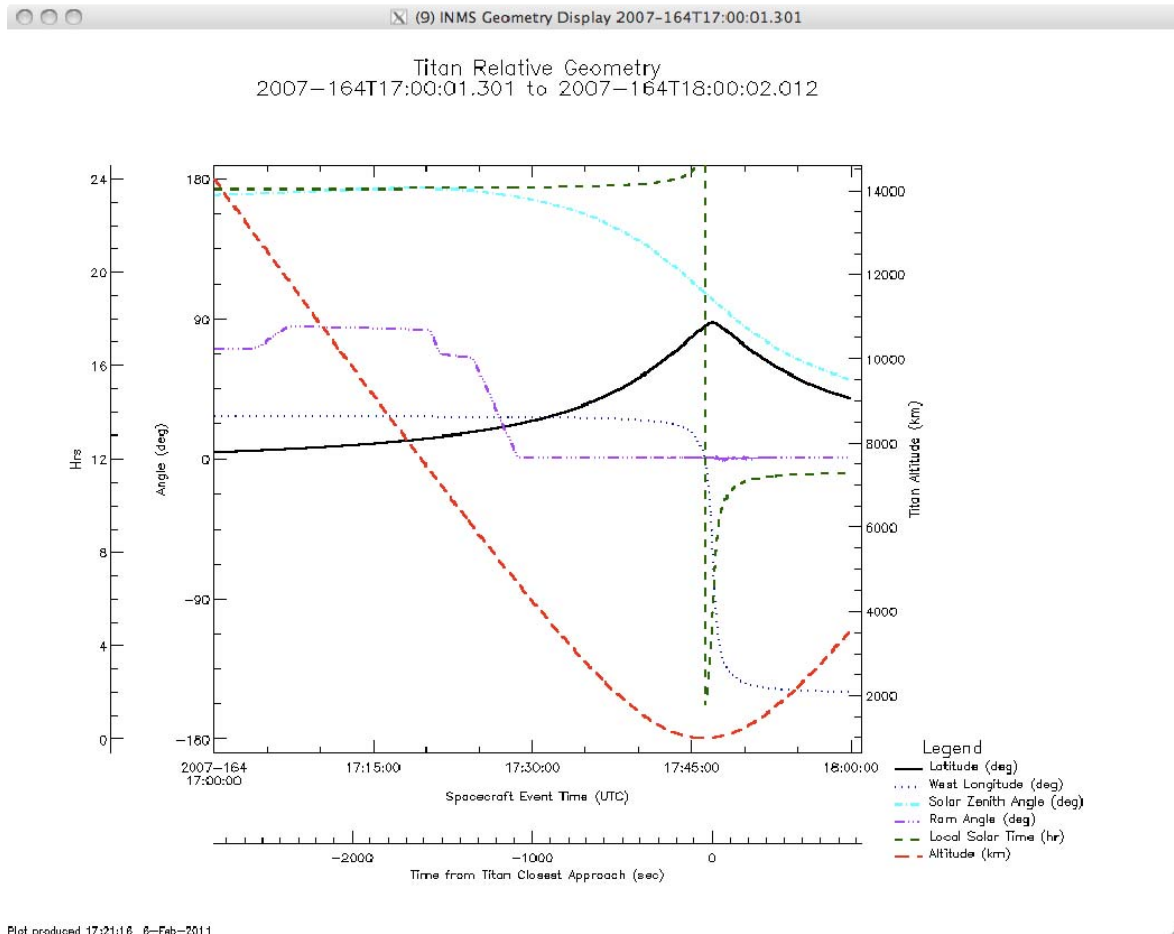
d) *inms\_plot\_histogram, axMean*

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, Figure 7, is for T5, hour 19, with mass tables 40 and 41 and altitude 0-2,000 km specified in *inms\_get\_spectra*.



**Figure 7** An example mass-spectrum histogram plot of T5 data using IDL routines. This example shows count rate for ions below 2,000 km altitude. Since the OSI mode was only used during egress, these are all egress data. INMS does not measure masses from 9 to 11 AMU, and the low count rate at these masses is the way the plotting routine treats non-existent data. This figure is an exact copy from the IDL analysis routines, and the label sizes—which are adequate for on-screen analyses—are small for print.

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 the closest approach.



**Figure 8** 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. By the end of 2012, the INMS intends to provide calibrated densities for

some ions. The team also intends to provide IDL routines that will calculate ion density. Even after densities and IDL routines are added to the INMS PDS site, this section provides information for additional analyses, if desired.

There are four steps, each with several calculations. All of the calculations depend on both the predicted and actual energy of the ions.  $V_{\text{COMP}}$  and anticipated spacecraft charging set the predicted energy, which determines the on-board instrument settings, particularly the voltages settings for the quadruple switching lens. The separation between the actual and predicted energies determines the efficiency of ion transmission. Since mass, velocities of the ions, and spacecraft charging all affect energy, they are necessary in converting count rate to density, and both the predicted and actual velocity and spacecraft potential are required. Finally, the coefficients used to convert the predicted energies to instrument voltages are settable and are non-constant parts of calibration.

For the earlier Titan passes, the INMS settings were different from the settings that were later determined to be optimal. Predicted velocities, predicted spacecraft charging, and quadruple voltage coefficients were all improved after T40. After describing detailed calculations for ion density, we will examine possible simplifications, some of which may only be applicable to later passes where the predicted parameters are close to the actual parameters.

### 1. Calculate the actual energy of the ions

The energy of the incoming ions in electron volts (eV) is

$$E = \frac{1}{2} m u^2 - C_0 m (\varphi_{S/C} - u_{\text{winds}})^2 - q \quad (1)$$

where  $m$  is the ion mass in AMU,  $u$  is the velocity (spacecraft or along-track winds) in km/s,  $\varphi_{S/C}$  is the spacecraft potential in volts, and the coefficient  $C_0$  is  $5.182 \times 10^{-3}$  for the specified units. At Cassini flyby velocities (6 km/s), no wind, and a spacecraft potential of -0.5 V, ion energies range from 0.9 eV for ions with a mass of 2 AMU to 19.0 eV for 99 AMU ions.

There are two important energies, the actual ion energy, which is required for all of the remaining density-calculation steps, and the predicted ion energy, which is only used to set the INMS voltages. Since the voltages are stored in the L1A file, we do not need to calculate the predicted energies. Indeed, neither the predicted energies nor the values needed to calculate them are stored in the L1A file or anywhere on the PDS, so the predicted energies cannot be calculated with contacting the INMS team.

(Some of the values used to calculate the predicted energies are in Mandt *et al.*, 2012. The spacecraft voltage was set to its most common value, -0.5V, only after T40. The spacecraft velocity was less predictable until after T40, too. Since the direction of the winds can be in any orientation with respect to Cassini's velocity, the predicted  $u_{\text{winds}}$  is always zero.)

The value for  $u_{S/C}$  is the X component of the spacecraft velocity in the L1A file. Although  $\phi_{S/C}$  can be derived from another Cassini instrument (RPWS), -0.5 V is a good value for altitudes below 1,400 km. The along-track wind velocity can only be estimated with extensive analyses involving both INMS and IBS data, so most researches do not correct for wind and then increase the uncertainty to account for the unknown parameter.

2. Calculate the optimal voltage settings

For each ion energy, there is an optimal set of quadruple voltages that transmits more ions at that particular energy than any other set of voltages. The actual transmission of ions depends on the separation between the optimal voltage settings and the as-flown voltage settings, which are based on the predicted energy of the ions. A single voltage,  $V_{QL3}$ , represents the quadruple voltages. (The other voltages have a fixed relationship to  $V_{QL3}$ .) The optimal value for  $V_{QL3}$  is

$$V_{QL3, optimal} = A_0 + A_1 E \tag{2}$$

where  $A_0$  and  $A_1$  are coefficients that were determined by in-flight calibrations based on energy scans, and  $E$  is the actual ion energy from step 1.

Transmission depends on the sensitivity of ion energy to the voltage separation, which is the width of the energy curve as determined by the energy scans. The width is

$$W = B_0 + B_1 E \tag{3}$$

where  $B_0$  and  $B_1$  are derived constants, listed below. At Titan flyby velocities, the width,  $W$ , is 0.6 V for the lower masses and 1.5 V for the highest masses.

Mandt *et al.* 2012 describes how the constants that convert energy to INMS voltage settings are determined using in-flight data from the energy scans. The values for the four constants are

- A0= -54.2 V
- A1= -0.86 eV/V
- B0= 0.651 eV/V
- B1= 0.260

3. Calculate the transmission loss

The efficiency of INMS measurement of ions, or the transmission loss, is well characterized by a Gaussian function:

$$T = \frac{1}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(V - \mu)^2}{2\sigma^2}\right) \tag{4}$$

with

$$V_{opt} = \frac{V_{flight} - V_{err}}{\tau} \quad (5)$$

where  $\tau$  is the transmission factor, a dimensionless parameter with  $\tau=1$  for optimal voltage settings,  $V_{err}$  is the voltage error scaled by the width of the error curve, and the subscripts “optimal” and “as-flown” refer to the optimal settings for the quadruple voltages and the flight settings, respectively. The optimal setting is calculated in step 2, above, and the as-flown setting is in the L1A data file.

Figure 5 shows a plot of how  $\tau$  varies as a function of  $V_{err}$ . When the flight settings are close to optimal, then transmission is close to one and the count rate is unaffected. If the ion energy is different from the predicted energy, then the optimal setting—which is based on actual data—is different from the flight setting and the count rate will be reduced by a factor of  $\tau$ . Since  $W$  increases with ion energy, similar errors in  $V_{QL3}$  produce a smaller  $\tau$  for heavier ions.

4. Calculate sensitivity and density

To convert the INMS measurements to density:

$$n = \frac{c}{tS\tau} \quad (6)$$

where  $c$  is the counts in a given IP (counts/IP) and corrected for dead time (see Section 3),  $t$  is the duration of an IP, 0.0311 seconds,  $n$  is the density in ions/cm<sup>3</sup>, and  $S$  is the sensitivity in [counts/s]/[ions/cm<sup>2</sup>/s], and is calculated by

$$S = C_1 + C_2 E \quad (7)$$

with the constants  $C_1 = 1.360 \times 10^{-3}$  and  $C_2 = 1.840 \times 10^{-4}$  for  $E$  in eV. These constants depend on details of the calibration that have been difficult to specify. In early 2012, the INMS determined that the constants presented here are the best values. They differ slightly from the values used in Cravens *et al.* 2006 and most other references before 2012.

Possible simplifications in density calculations

There are several approaches to simplifying the analyses. See Section 2.3 to understand the effect of these simplifications on density measurements.

- Limit analyses to the lower-altitude data, below 1,300 km or 1,400 km, where the winds are lower and the spacecraft potential is usually close to -0.5 V. There is no need to carry additional uncertainty due to possible higher winds or due to large variations in spacecraft potential.
- Limit analyses to Titan passes after T40, where the predicted energies (the flight  $V_{QL3}$ ) are close to the actual energies (the optimal  $V_{QL3}$ ). This is because the predicted velocities are more accurate, the spacecraft voltage is set to -0.5 V, and the on-board coefficients A0 and A1, which set  $V_{QL3flight}$ , are close to the optimal values.

If using both of these simplifications, then researchers can assume a value of 1 for  $\tau$  and use an uncertainty of 15-20%, depending on mass, to account for the simplifications. However, if there are large, rapid excursions or variations in density, then it is necessary to check the spacecraft voltage as a possible cause.

### 2.2.5 Available auxiliary data

The L1A file contains most of the observation-specific data required for analyzing the INMS OSI measurements. The table, below, contains most of the variables used during INMS analysis. 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. To reduce uncertainty as much as possible, data from other instruments can help. Unfortunately, they are processed data and not yet available at the PDS site. Spacecraft potential can be obtained by analyzing RPWS Langmuir probe data and along-track winds can be obtained by comparing the IBS energy spectrum to INMS OSI data. The second analysis, in particular, is difficult and requires extensive knowledge of both instruments. The INMS team plans to supply these data as higher-level data products in the future.

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. Nearly all ions have a single charge.
<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)	The x component is the proper velocity to use for calculating the actual energy. The y and z components can be used to determine the angular offset
<i>time_ca</i>	Time in milliseconds from closest approach	
<i>coadd_cnt</i>	Number of measurements (IPs) binned together on board	Convert the number of counts to counts per IP. Most Titan data have <i>coadd_cnt=1</i> , but must check.
$V_{COMP}$	Velocity compensation. The predicted velocity of Cassini through the atmosphere	Used to determine the predicted energy for setting $V_{QL3}$ and the other INMS voltages
<i>qp_lens3</i>	$V_{QL3}$ , the voltage on the third lens of the quadrupole	Used as a reference for all the quadrupole voltages, which determine the energy of the admitted ions
<i>alt_t</i>	Altitude from surface of the target	Height in the ionosphere
<i>source</i>	INMS mode	This users' guide describes analysis of data measured while in the OSI mode
<i>sc_pos_t_x</i> <i>sc_pos_t_y</i>	Position of Cassini in the xyz reference frame of the target	Latitude and longitude are derived from these parameters

<i>sc_pos_t_z</i>	body	
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### 2.3 Overview of uncertainty

#### *Statistical uncertainty*

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 counts, 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 fractional uncertainty is lower. 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.

This statistical uncertainty only applies to the measured number of counts. In converting the counts to density, or in applying the correct voltage settings, there are additional uncertainties, including the uncertainty in the spacecraft potential and the wind speed and direction.

#### *Energy uncertainty*

Ion energy is uncertain due to winds (ion drifts with respect to the Titan-centered frame of reference) and spacecraft potential. Ion energy also depends on spacecraft velocity, but its uncertainty, at a fraction of a percent, is negligible.

From the energy equation in Section 2.2.4, part 1, errors in spacecraft potential translate directly to errors in energy. The nominal spacecraft voltage of -0.5 V is usually accurate to a few tenths of a volt at altitudes below 1,300 km (Cui *et al.*, 2009). At higher altitudes, 2-volt excursions in spacecraft potential have been measured, so limiting research to lower altitudes limits uncertainty due to spacecraft voltage. From the  $V_{err}$  equation in part 2, the effect of voltage errors depends on  $W$ , the width of Gaussian transmission function. At Titan flyby velocities, the width is 0.6 V for the lower masses and 1.5 V for the highest masses. An error in spacecraft potential of 0.5 V causes an error in the scaled voltage error  $V_{err}$ , of 1.0 to 0.3 for the lower and higher masses, corresponding to transmission losses ( $\tau$ ) of 40% to



5%. In the most extreme cases, INMS ion count rate has fallen more than three orders of magnitude due to a 2-volt increase in spacecraft potential.

Similar to the spacecraft voltage uncertainty, wind uncertainty is lower below 1,300, where the maximum winds are 100 m/s. At higher altitudes, winds of 300 km/s have been modeled. Cassini's velocity through Titan's ionosphere is approximately 6 km/s, so a 100 m/s uncertainty equates to an uncertainty in the energy of 3%, and 300 m/s corresponds to 10%. Tracing a 3% energy uncertainty through the equations in Section 2.2.4 parts 2 and 3, with no other differences,  $V_{err}$  will be 0.03 to 0.3, depending on mass. An estimate of the along-track winds can be extracted from a detailed comparison of INMS and IBS data, but researchers usually incorporate winds into the overall uncertainty.

Due to larger uncertainty associated with higher altitudes, some researchers limit their studies to altitudes below 1,300 km or 1,400 km.

#### *Cross wind*

The wind velocity may be in any direction with respect to Cassini's trajectory. Cross winds do not affect ion energy, but they shift the intercept angle of the ions away from the INMS boresight. A 100 m/s crosswind puts the ions about 1 degree from the boresight. Since the INMS FOV for ions can be just 2 or 3 degrees for the highest masses, this crosswind can cause factor-of-two decrease in count rate (see Figure 2). A higher crosswind of 300 m/s can push high-mass ions completely out of INMS's FOV. There are no Cassini data that can be used to estimate the crosswind, so this is an uncertainty that cannot be refined with data.

#### *Stacked uncertainties*

Two different errors in predicted energy can cancel each other and result in little degradation in transmission. For example, a head wind can counter an error in the spacecraft voltage. Errors do not add linearly, however, as seen in Figure 5. A  $V_{err}$  of 0.3 only reduces  $\tau$  by 3.5% if there are no other errors. However, that same  $V_{err}$  of 0.3 causes an additional 17% loss in transmission if it is stacked onto another error that had already created a  $V_{err} = 1.0$ . The effect of crosswinds is separate, and they always reduce transmission, with larger effects for higher masses due to their smaller FOV.

### **3 Additional example analyses without IDL**

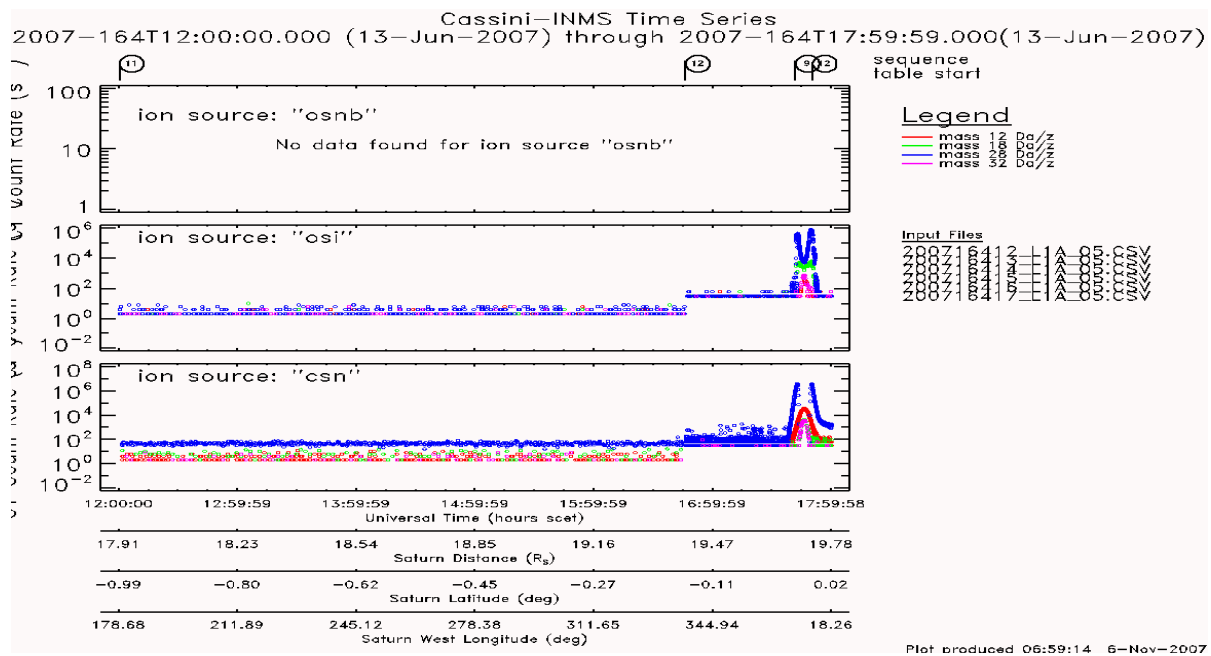
This section describes how to use the information in Section 2.2.4 to reproduce two figures in the first Titan-ion paper, Cravens *et al.* 2006. Figure 10 is a mass spectrum for the Titan flyby on T5 (Cassini's fifth orbit of Saturn) and Figure 11 is the ion densities vs. altitude for two of the higher-density ions at masses 28 ( $\text{HCNH}^+$ ) and 41 ( $\text{C}_3\text{H}_5^+$ ). 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 with the exception of some coefficients that are in this guide in Section 2.2.4. Counts, instrument settings, spacecraft position and attitude, velocities, and timing are in the L1A data file. Other necessary data are in the housekeeping data file (see Section 2.2.3).

For the mass spectrum example, we use both simplifying assumptions at the end of Section 2.2.4 and assume that the transmission is 1.0. The data are for lower altitudes, so they meet the first simplifying requirement. However, the second simplifying requirement is not met: T5 was an early pass,  $V_{QL3flight}$  was predicted incorrectly, and the transmission function is less than 1. The mass spectrum would be improved by incorporating the correct transmission. For the time-history example, we perform all the steps in Section 2.2.4 to get the best possible result.

Before providing the two examples, we first describe how to locate the proper data file for analysis and how to modify the high count rates to adjust for dead time in the detector.

*Identifying the data files*

There are two quick ways to identify the files containing the data at closest approach. Any list of Titan passes (e.g., an appendix of this guide) provides the time of closest 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 Figure 9 for T32 also show the time of close approach, and from the browse plot, it is clear that the Titan pass occurs between the times of 17:00 and 18:00. Therefore, the data are in the INMS data file that covers 1700-18:00, filename 200716417\_L1A\_05.CSV.



**Figure 9.** An example summary plot that includes the T32 encounter. This is a copy of one of the browse plots so the labels are small.

*Adjusting the raw counts: correction for dead time*

Many particle-counter detectors require a short time to recharge after counting a particle. If another particle hits the detector while it is recharging, it may not be detected. The term

“dead time” is related to this recharging time. For higher count rates, above  $1 \times 10^4$  counts/IP, the effect of detector dead time becomes a few percent and the counts should be adjusted before converting them to density. (Ion analyses do not require the other corrections that are required for neutral analyses such as saturation, thruster contamination, high pressure, and wall adsorption.) For the count rates for ions in T5, approximately  $2 \times 10^4$  per IP, the maximum adjustment due to dead time is less than 3%.

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

$$C_m = C_t \times e^{(-C_t \times t_d)} \quad (8) \text{ (from Magee } et al. \text{ 2009, Eq 3)}$$

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 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  $C_t = C_m \times e^{(C_m \times t_d)}$ , which is a convenient form for calculations. Additional details are described in the Magee *et al.* 2009 treatment of neutrals, which have a higher count rate than ions. Since the ion count rate is seldom higher than  $4 \times 10^4$ , the above equation is adequate for ion analyses.

### 3.1 Mass spectrum: density vs. mass

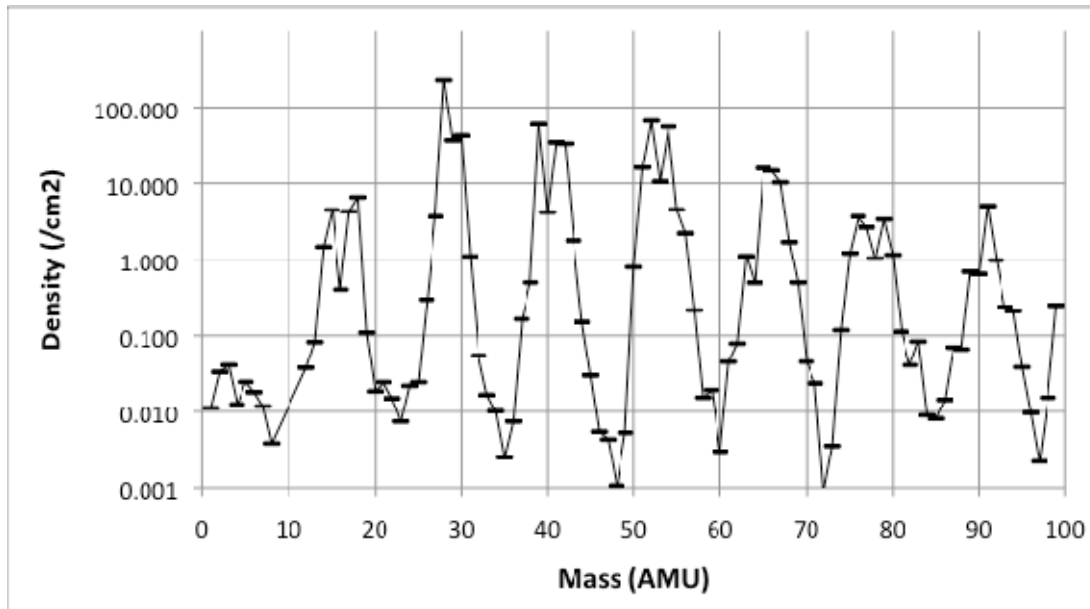
For the mass spectrum plot, we use the simplifying assumptions described at the end of Section 2.2.4:

- Spacecraft potential is -0.5 V, which is likely a good assumption.
- $V_{err}$  is zero so the transmission function is 1.0. This assumption is not valid, and the next section describes the effect of this assumption.

With a transmission value of 1.0, the density in part 4 of Section 2.2.4 depends only on the sensitivity ( $S$ ), energy ( $E$ ), and the spacecraft velocity ( $u_{S/C}$ ). Since  $E$  depends only on mass and  $u_{S/C}$ , density depends only on those two variables.

To calculate the mass spectrum, the data file is clipped to include only the times and INMS modes of interest. In this case, only data rows where the altitude is below 1,200 km and the source is OSI are retained. In the L1A file, these are the *alt\_t* and *source* columns. The data are then sorted or grouped by mass, which is the *mass\_per\_charge* column, and the counts are averaged for each mass. The spacecraft velocity, *sc\_vel\_t\_scx*, varies by less than 0.5%,

so we take it as a constant. Next, the energy for each mass is calculated using the equation in part 2 of Section 2.2.4 and the simplifying assumption that the spacecraft potential is -0.5V. Finally, the sensitivity and density for each mass are calculated using equations in part 4 of Section 2.2.4. Figure 10 shows the result, which can be compared to the red curve in Figure 3 of Cravens *et al.* 2006.



**Figure 10.** This Microsoft Excel plot shows the ion mass spectrum for Titan flyby T5 for the altitudes between 1,027 km and 1,200 km. The lower limit of the altitude corresponds to the lowest altitude measured with the OSI mode during T5. This plot can be compared to the red line in Figure 3 of Cravens *et al.* 2006 (the red line was multiplied by 100 to reduce clutter in the figure). There are several slight differences between the two figures. The coefficients for calculating sensitivity have been revised since 2006. The assumption for spacecraft potential may be different, also.

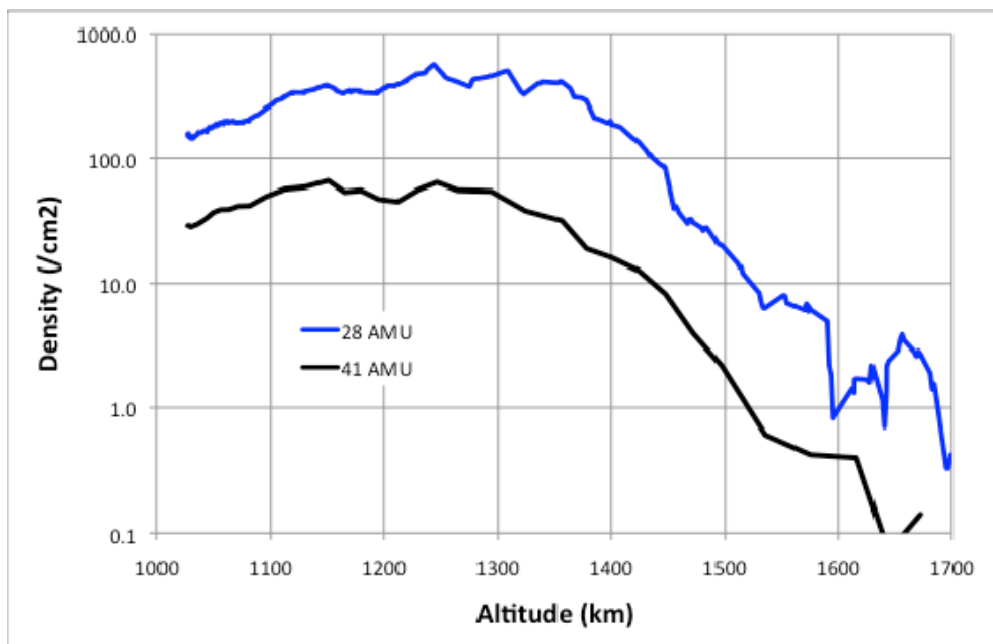
### 3.2 Densities and altitude dependence of individual species

Here, we derive the densities for the Titan flyby T5 for two major ions,  $\text{HCNH}^+$  and  $\text{C}_3\text{H}_5^+$ . The differences between this and the mass-spectrum calculations in the previous section are that we do not assume that the transmission factor is 1.0 and that we calculate the time-dependent variation in transmission.

Transmission falls below 1.0 when the flight values for  $V_{QL3}$  are different from the flight value, which is found in the L1A file in the *qp\_lens3* column. The optimal setting for  $V_{QL3}$  requires the flight velocity, which is in the L1A file, and the spacecraft potential, which is best obtained from the RPWS. For flybys before T41, the on-board coefficients required to calculate  $V_{QL3}$  had not been corrected, so the flight  $V_{QL3}$  was usually different from the optimal value.

The steps to create Figure 11 are

1. Import the data from 200510619\_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 all rows that are not OSI data.
4. Delete all data from above 1,700 km: all data with  $alt\_t > 1700$
5. Sort the data by mass
6. Delete all masses other than the desired species, masses 28 and 41 for this plot.
7. Correct the counts for dead time
8. Calculate the energy and sensitivity for the desired masses. If spacecraft potential and velocity are constant during the period, then these calculations are only needed once for each mass.
9. Calculate  $V_{QL3optimal}$  for each mass, and then subtract from the flight value ( $V_{QL3flight}$ , which is  $qp\_lens3$  stored in the L1A file) to get  $V_{err}$ . As with the previous step, we only need to do this calculation once per mass if all the parameters are constant. In addition to potential and velocity,  $qp\_lens3$  constant, too.
10. Calculate the transmission for each mass.
11. Use transmission, sensitivity, velocity, and count rate to calculate density.



**Figure 11.** This example of analyzing Titan ions can be compared to Figure 2 in Cravens et al. 2006 analysis of T5 ions. As with Figure 10, there are some known differences in the analyses, including different coefficients for sensitivity and for the optimal voltage settings. Mass 28 was measured more often than mass 41 and has higher spatial resolution. The densities in this plot include corrections for transmission loss due to non-optimal settings in flight.

#### *Additional possible corrections*

There are three possible, additional corrections that could be applied to these densities.

- If spacecraft voltages are available, they can be used in place of the assumed -0.5 V, improving the energy and transmission estimates. The Langmuir probe on RPWS is the best source for spacecraft voltage.
- Although the analysis is difficult, comparison of IBS and INMS data provides a means to estimate along-track winds and their effect on ion energy. In the future, these winds may be available on the INMS PDS site as a higher-order data product.
- Usually, there is a small cross-track component to Cassini's trajectory, and that can reduce count rate due to INMS's narrow FOV in the OSI mode. Data in the L1A files provide the spacecraft velocity with respect to the ionosphere and the angle of the INMS boresight with respect to the velocity. The relevant spacecraft-attitude variables are  $sc\_vel\_t\_scx/y/z$ . When INMS is pointed in the ram direction,  $sc\_vel\_t\_scx$  is the velocity of the spacecraft through Titan's ionosphere and the other two components are components of the perpendicular velocity. The deviation from boresight is the angle whose tangent is  $sc\_vel\_t\_scyz / sc\_vel\_t\_scx$ , where  $scyz$  refers to the component of velocity in the YZ plane. For T5, the incident angle is about 0.4 degrees, which is negligible except for the highest masses, which have an FOV of 2 degrees.

#### 4 Cautions for analyzing Titan ion data

- **Calibration changes** – There have been several adjustments in INMS calibration. The calibration steps and constants in Section 2.2.4 are based on Mandt *et al.* 2012, which has a full description of OSI calibration.
- **Incorrect settings for early passes** – The voltage settings before T41 frequently deviated from the nominal values so that transmission was less than 1.0. Since transmission errors accumulate non-linearly, these incorrect settings can magnify the effect of other errors such as spacecraft potential and along-track winds.
- **Spacecraft potential** – Below 1,300 km, spacecraft potential is usually within a few tenths of a volt of -0.5V, but higher altitudes may have excursions that reduce INMS count rate by a factor of 1,000 (see T32 inbound data). High-accuracy analyses require examination of the spacecraft potential.
- **Along-track winds** – Along-track winds can increase or decrease transmission, depending on other errors.
- **Crosswinds** – These are not known and produce the largest uncorrectable errors in ion densities derived from INMS ion data.
- **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

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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 papers

Mandt *et al.*, 2012, Ion densities and composition of Titan's upper atmosphere derived from the Cassini Ion Neutral Mass Spectrometer: analysis methods and model comparison. In preparation.

Waite *et al.* 2012, In-flight and ground calibration of the Cassini Ion Neutral Mass Spectrometer: determination of the calibration constant required for calculation of ion and ambient neutral densities and related uncertainties. In preparation.

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 ion analyses**

Cui *et al.*, 2009, Diurnal variations of Titans' ionosphere. *Journal of Geophysical Research*, 114, A06310.

Cravens *et al.*, 2006, Composition of Titan's ionosphere. *Geophysical Research Letters*, 33, L07105.

Mandt *et al.*, 2012, Ion densities and composition of Titan's upper atmosphere derived from the Cassini Ion Neutral Mass Spectrometer: analysis methods and model comparison. To be submitted.

Vuitton *et al.*, 2007, Ion chemistry and N-containing molecules in Titan's upper atmosphere. *Icarus*, 191, 722-732.

- **Guide to INMS IDL routines**

The 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  
[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)
- **Titan neutral analyses**  
Perry, Mark E., 2011, Users' guide for analyzing INMS data on Titan's neutral atmosphere, Planetary Data System documentation.  
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



## 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
	taug_pos_x	Other Kernels	SCAN	position of the target body in the IAU Saturn reference frame	real	km	$bd \leq 10^7$	F9.0
	taug_pos_y	Other Kernels	SCAN	position of the target body in the IAU Saturn reference frame	real	km	$bd \leq 10^7$	F9.0
	taug_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		csn 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		xs0	I4
	table_set_id	OTS	SCAN	table set ID number	string			C8
	coadd_cnt	nDataSum	SCAN	specifies the number of IPs 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		$1 \leq x \leq 64$	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		$1 \leq x \leq 64$	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		$1 \leq x \leq 96$	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

Part 2

	name	where from	store in	description	type	units	range	format
	p_energy	Calc	P	Particle Energy	real	eV		F7.3
	alt_t	Other Kernels	P	altitude above the surface of the named target body	real	km	$bd \leq 10^5$	F9.2
	view_dir_t_x	C-Kernels	P	components of the unit vector in the direction of the INMS aperture outward normal .	real		$bd \leq 1$	F9.6
	view_dir_t_y	C-Kernels	P					
	view_dir_t_z	C-Kernels	P					
	sc_pos_t_x	Other Kernels	P	x component of spacecraft position wrt the named target	real	km	$bd \leq 10^5$	F9.2
	sc_pos_t_y	Other Kernels	P	y component of spacecraft position wrt the named target	real	km	$bd \leq 10^5$	F9.2
	sc_pos_t_z	Other Kernels	P	z component of spacecraft position wrt the named target	real	km	$bd \leq 10^5$	F9.2
	sc_vel_t_x	Other Kernels	P	x component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_t_y	Other Kernels	P	y component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_t_z	Other Kernels	P	z component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_t_scx	Other Kernels	P	spacecraft frame x component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_t_scy	Other Kernels	P	spacecraft frame y component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_t_scz	Other Kernels	P	spacecraft frame z component of spacecraft velocity wrt the named target	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	lst_t	C-Kernels	P	local solar time at the sub-spacecraft point on the target body	real	hours	$0 \leq x \leq 24$	F6.3
	sza_t	C-Kernels	P	solar zenith angle at the sub-spacecraft point on the target body	real	deg	$0 \leq x \leq 180.$	F7.3
	ss_long_t	C-Kernels	P	longitude of the sub-solar point on the target body on the target body	real	deg	$0 \leq x \leq 360.$	F6.2
	distance_s	Other Kernels	P	distance between spacecraft and center of Saturn	real	km	$bd \leq 10^7$	F9.0
	view_dir_s_x	C-Kernels	P	components of the unit vector in the direction of the INMS aperture outward normal	real		$bd \leq 1$	F9.6
	view_dir_s_y	C-Kernels	P					
	view_dir_s_z	C-Kernels	P					
	sc_pos_s_x	Other Kernels	P	x component of spacecraft position	real	km	$bd \leq 10^7$	F9.0
	sc_pos_s_y	Other Kernels	P	y component of spacecraft position	real	km	$bd \leq 10^7$	F9.0
	sc_pos_s_z	Other Kernels	P	z component of spacecraft position	real	km	$bd \leq 10^7$	F9.0
	sc_vel_s_x	Other Kernels	P	x component of spacecraft velocity	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_s_y	Other Kernels	P	y component of spacecraft velocity	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	sc_vel_s_z	Other Kernels	P	z component of spacecraft velocity	real	km s <sup>-1</sup>	$bd \leq 100$	F7.3
	lst_s	C-Kernels	P	local solar time at the sub-spacecraft point on Saturn	real	hours	$0 \leq x \leq 24$	F6.3
	sza_s	C-Kernels	P	solar zenith angle at the sub-spacecraft point on Saturn	real	deg	$0 \leq x \leq 180.$	F7.3
	ss_long_s	C-Kernels	P	longitude of the sub-solar point on the target body on Saturn	real	deg	$0 \leq x \leq 360.$	F6.2
	sc_att_angle_ra	C-Kernels	P	right ascension of spacecraft z axis	real	rad	$0 \leq x \leq 2\pi$	F9.6
	sc_att_angle_dec	C-Kernels	P	declination of spacecraft z axis	real	rad	$-\pi/2 \leq x \leq \pi/2$	F9.6
	sc_att_angle_tw	C-Kernels	P	rotation of spacecraft about z axis	real	rad	$0 \leq x \leq 2\pi$	F9.6
	c1counts	C1Counters	SCI	high sensitivity counts	int		$0 \leq x \leq 10^6$	I6
	c2counts	C2Counters	SCI	low sensitivity counts	int		$0 \leq x \leq 10^6$	I6

## 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. The table contains only flybys with minimum altitudes below 1,500 km with useful INMS pointing (-X in the ram direction). 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

<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
T-71	2010-188	00:22:45	1005
T-77	2011-171	18:32:01	1359
T-83	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

### 6.3 Glossary and acronyms

- AMU: atomic mass unit. H<sub>2</sub> is 2 AMU, CH<sub>4</sub> is 16 AMU.
- CAPS: Cassini plasma spectrometer. A suite of instruments that measures low-energy ions and electrons.
- *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.
- CSN: the Closed Source Neutral mode for INMS. Measures neutrals using the closed-source aperture.
- Dalton: equivalent to AMU.
- eV: electron volts, a unit of energy
- FOV: field of view; 2-5 degrees for the OSI mode, depending on mass.
- IBS: ion beam spectrometer, the CAPS instrument that measures ion energies.
- INMS: Cassini's Ion and Neutral Mass Spectrometer
- IP: integration period. 31 millisecond, the duration of each measurement period where INMS counts particles with a designated mass and energy.
- 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.
- mass table: one of a set of tables uploaded to the INMS that determines the masses—and their order—that INMS measures.
- OSNB: open source neutral beam, the INMS mode used to measure neutrals through the open source aperture
- OSI: open source ion, the INMS mode used to measure ions.
- QL3: the index for the third quadrupole switching lens. The QL3 voltage is used to represent INMS energy settings because the voltages for the other quadrupole lens are based on  $V_{QL3}$ .
- Ram angle: the angle between the INMS boresight and the velocity vector of particles measured by INMS
- RPWS: radio and plasma wave science instrument on Cassini. Includes a Langmuir probe that is the source of data on spacecraft potential
- SIS: Software Interface Specification, a PDS document that describes data for a particular instrument
- $T_n$ : the  $n^{\text{th}}$  flyby of Titan
- VCOMP: the INMS velocity compensation parameter, which is the predicted velocity of the measured particles with respect to INMS. Approximately 6 km/s for Titan flybys.