CCSDS Tracking Data Message Early Implementation Experiences

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Abstract

The Consultative Committee for Space Data Systems (CCSDS) produces recommendations for standards that aim to increase interoperability between the world's space agencies and space operators. One such standard is the CCSDS Tracking Data Message (TDM), which describes a standardized format for the exchange of spacecraft tracking data. Since its formal completion and release in late November 2007, there have been two operational versions of the TDM used (a) between the European Space Agency's Space Operations Center (ESA/ESOC) and the National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA/JPL) and (b) between the Indian Space Research Organization (ISRO) and NASA/JPL.

The first implementation was limited to the exchange of Delta Differential One-Way Ranging data (Delta-DOR) between ESA/ESOC and NASA/JPL for NASA's Phoenix mission to Mars.

The second implementation expanded the NASA/JPL implementation to include the range data type and the transmit/receive frequencies data types (used for computation of the Doppler observable). This second implementation applied to ISRO's Chandrayaan-1 mission to the Moon.

This paper will discuss some practical issues that were encountered implementing the standard, and discuss potential future implications of using the TDM. Using a standard such as the TDM will allow agencies to support interagency tracking at lower cost, and on reduced schedule, without requiring use of software developed by other agencies. The TDM can be implemented by any given space agency in any programming language they prefer, on any operating environment, independent of implementations in other agencies.

Background

The CCSDS is an international standards organization, part of the International Organization for Standardization (ISO) [1]. CCSDS represents the ISO Technical Committee 20 (Aircraft and Space Vehicles) Subcommittee 13 (Space Data and Information Transfer Systems).

The technical domain of the CCSDS is divided into 6 Areas, one of which is the Mission Operations and Information Management Services (MOIMS). Each of the CCSDS Areas is further divided into smaller entities known as Working Groups (WG), Birds of a Feather groups (BOF) or Special Interest Groups (SIG). The Working Group is the entity with the most formal existence, having been chartered by the CCSDS Management Council to develop standards within a specific segment of the CCSDS domain. One such Working Group is the Navigation Working Group, which is part of the MOIMS Area. [2]

The CCSDS Navigation Working Group is chartered to provide a forum for the development of flight dynamics related standards [3]. At present, there are 4 standards that are part of the Navigation Working Group Technical Program, as follows:

- Orbit Data Messages, CCSDS 502.0-B-1 [4]
- Tracking Data Message, CCSDS 503.0-B-1 [5]
- Attitude Data Messages, CCSDS 504.0-B-1 [6]
- Navigation Data Messages / XML Specification, CCSDS 505.0-R-2 [7]

This paper will discuss early implementation experiences with one of these standards, the Tracking Data Message (TDM) [5]. The TDM was the second of the standards developed by the CCSDS Navigation Working Group to complete the full CCSDS Standards Development Process (described in [8]). The development of the TDM standard began late in 2003, and was completed in November 2007.

One of the most challenging aspects of the standards development process is obtaining the commitment to implement them by space missions and/or the agencies that sponsor them. This is likely a combination of influences including a natural human resistance to change in general, risk aversion on the part of space agencies, and budgetary concerns. Nevertheless, at last count (as of January 2009), 416 missions have incorporated CCSDS standards in some aspect of their operation. [9]

TDM Overview

The TDM standard specifies a standard ASCII-based message format for use in exchanging spacecraft tracking data between space agencies. Such exchanges are used for distributing tracking data output from interagency cross-supports in which spacecraft missions managed by one agency are tracked from a ground station managed by a second agency. Tracking data includes data types such as Doppler, transmit/received frequencies, range, angles, Delta-DOR, media corrections, weather, etc. The standardization of tracking data formats facilitates space agency allocation of tracking sessions to a more diverse set of tracking resources.

One primary emphasis in the development of the TDM was to make the format and definition of tracking data as independent as possible from the particular equipment that was used to generate it. The generator of the message needs to convert the raw measurements into navigation observables in metric units, so the user does not need to know how the equipment operates in order to be able to use the data. Examples of this are the use of sky-level values for frequencies, and the recommendation that any equipment-dependent calibration should be applied by the generator of the TDM, and not passed along to the user.

The content of a TDM instantiation is separated into three basic structural elements: a header which provides identifying information, a metadata section which provides a description of the data contained in the message, and a data section that contains the data itself. The ASCII text in a TDM can be exchanged in either of two formats: a “keyword-value notation” format (KVN) or an XML format. The KVN formatted message is described in [5]. Description of the message format based on XML is detailed in an integrated XML schema document for all Navigation Data Messages [7].

Prototyping of the TDM

Before a CCSDS standard is finalized, the CCSDS Standards Development Process [8] calls for draft standards to be tested using two or more operational prototypes. For these prototypes, the operations environment may be real or simulated. In the case of the TDM, there were three space agencies (ESA/ESOC, NASA/JPL, and the Deutsches Zentrum für Luft- und Raumfahrt (DLR)) that participated in the TDM prototyping [10]. The implemented prototypes were completely independent, based as they were on the software conventions of the three participating agencies. According to the design principles of the TDM, the prototype software was not exchanged. Only the output of the prototypes was exchanged, i.e., only the formatted tracking data itself. While the prototypes were not required to be operationally robust, these parallel efforts demonstrated the feasibility of the TDM and the relative ease with which an implementation could be developed.

Implementation #1: Use of the TDM in NASA’s Phoenix Mission

During the planning for NASA’s Phoenix mission to Mars, there was an agreement between NASA and ESA to perform interagency Delta-DOR tracking [11, Chapter 4] of the Phoenix spacecraft as it approached Mars. For this tracking campaign, NASA/JPL’s Delta-DOR tracking would be supplemented with Delta-DOR data collected using the tracking stations of ESA’s tracking network (ESA/ESTRACK [12], [13]). In April 2007, during operations planning discussions between ESA and NASA/JPL, it was determined that the data collected during ESA’s Delta-DOR observation campaign would be delivered to NASA/JPL in the TDM format. Because this direction was set prior to the completion of the TDM standard, there was considerable motivation to complete the standards development process according to the schedule dictated by the Phoenix mission’s planned Delta-DOR observation campaign. This was a significant vote of confidence in the feasibility of the TDM concept.

Because of the short time between the confirmation of the international standard in November 2007 and the Phoenix Delta-DOR observation campaign scheduled for January to March

2008, the first implementation of the TDM was of a quite reduced scope. A mission-specific (Phoenix), data-type specific (Delta-DOR), and very focused implementation was necessitated. The budget for the development was also quite small, as it was drawn from the budget allocated to support all activities of JPL's Navigation Standards task. This was neither an ideal funding scenario nor development scenario, however, given the general difficulty of gaining consent to infuse new standards into mission operations it was an opportunity that could not be ignored.

The strategy selected for the Phoenix Delta-DOR implementation involved ESA's conversion from its agency format IFMS [15] into the international exchange format (TDM), transfer of the data via SFTP, and NASA/JPL's conversion from the international exchange format into the TRK-2-18 tracking data format [14] currently used by most JPL navigation teams. This approach is cost-effective given that established agencies have invested considerable resources in building tracking networks that output data in agency specific formats such as JPL's TRK-2-18 and TRK-2-34 [19] and ESA's IFMS.

Though this first implementation of the TDM was mission-specific and data type specific, in design discussions there was a stated desire for an implementation that was "as generic as possible". This was based on an indefinite plan to ultimately extend the implementation to cover all of the TDM data types.

The first implementation of the Delta-DOR TDM was not completely without incident. During the checkout phase, analysis of test data revealed that some of the conventions with respect to the synchronization of clocks between tracking stations would require some minor re-wording in the TDM. (The Delta-DOR accuracy of the technique is critically dependent upon knowledge of the clock offsets between the station clocks at the two tracking stations.) First, when the timetag of the clock offset was exactly equal to the timetag of the data observation, the clock offset was not processed in the NASA/JPL software, causing large errors in the observable. Second, a reversal in the ordering of the stations in the determination of the station clock offsets from UTC caused a difference of signs between the ESA TDM writer and the JPL TDM reader. These issues had not arisen in the prototyping process. Once corrected in the reader/writer converters, these errors did not occur in the data collection campaign and the data collected by ESA was used without incident. Modifications to clarify the text of the TDM in the relevant document sections have not yet been implemented, but will be undertaken in the near future.

See Figure 1 for an example of a TDM that contains Delta-DOR data. This same figure also appears in the TDM document itself ([5], figure D-11), but here it has been modified to reflect the Phoenix experience noted in this paper. Specifically, there are two changes from the original figure: (1) the timetag on the "CLOCK_BIAS" keyword has been modified such that it is prior to the start of the first data point (arbitrarily one minute in this case), and (2) a second "CLOCK_BIAS" keyword corresponding to the final data point has been removed. Given the general stability of station clocks and the UTC standard, it is unlikely that there will be sufficient clock drift during a typical Delta-DOR measurement session to cause an accuracy problem in the observable. The changes shown in Figure 1 below will be reflected in a future version of the TDM standard.

Implementation #2: Use of the TDM in ISRO's Chandrayaan-1 Mission

In late 2007 the Indian Space Research Organization (ISRO) negotiated with JPL's Navigation Section for backup "shadow" navigation of the Chandrayaan-1 mission to the Moon. This shadow navigation effort involved activities such as review of the mission trajectory, review of the maneuver designs; and support of launch, cruise, lunar orbit insertion, and establishment of the science orbit. This involved exchanging and processing tracking data, parallel orbit determination, generation of backup ephemerides, and generation of backup maneuver designs.

The ISRO Chandrayaan-1 tracking plan called for the utilization of a variety of tracking resources, including the ISRO deep space stations at Bangalore (IDSN) [16], NASA/JPL's Deep Space Network (DSN) [17], the Johns Hopkins University Applied Physics Laboratory (JHU/APL) [18], the United Space Network (USN), and possibly others. Given this large number of disparate tracking assets, and the various tracking data formats involved, it was agreed that the exchange format between ISRO and NASA/JPL would be the CCSDS TDM. There was a short time frame, about three months, to develop and test the required conversion programs. JPL's existing ESA/Phoenix TDM code could not be used without modification because it was Delta-DOR specific and this data type was not part of the tracking requirements for Chandrayaan-1. Rather, the Chandrayaan-1 tracking requirements involved the exchange of uplink frequencies, downlink frequencies, and range data (see Figure 2 and Figure 3 for example TDMs that contain these data types). In addition, JPL's ESA/Phoenix Delta-DOR code had no capability to produce a TDM; it could only read a TDM. However, existing JPL TDM reader source code was used as a baseline for the Chandrayaan-1 implementation because it already contained the fundamental code required to parse the major sections of the message (header, metadata, and data) and parse the keywords within those major sections of the message.

As part of the preparations for the JPL support of Chandrayaan-1, there were several technical workshops conducted at Bangalore, India. At the second workshop, JPL presented a detailed description of the TDM and provided DSN tracking data of a NASA mission in a TDM file. Within a day of discussing the structure and content of the TDM the ISRO navigation team prepared working prototypes to (1) read the DSN data provided by JPL and (2) provide ISRO tracking data in the TDM format. In the absence of the TDM, it would have been necessary to implement one or more of the following complex and time consuming options:

- ISRO develop a TRK-2-18 reader/writer
- ISRO develop a TRK-2-34 reader/writer
- JPL develop an ISTRAC reader/writer

Such processors would not necessarily be re-useable in the support of missions with other agencies, whereas a TDM implementation, once developed, can form at least the foundation for the extensions that may be necessary to process tracking data produced by another agency. As such, the TDM represents a choice that is much more efficient in terms of the utilization of agency resources. In the words of one member of the JPL Chandrayaan-1 navigation team, "the TDM came along just in time. Use of the TRK-2-18 or TRK-2-34 would have been much more difficult to implement especially in the limited time available before pre-launch testing and mission operations”.

One of the lessons learned with the Chandrayaan-1 mission was that the ISRO range and Doppler conventions were not well understood, and it was necessary to be very clear on these conventions in order to correctly process the data. JPL’s Chandrayaan-1 navigation team spent quite a bit of time working out the necessary conversions from the data in the ISRO TDMs into the internal format utilized by the JPL orbit determination software.

Future Uses of the TDM

In the future, the DSN has plans to offer missions the option to have their tracking data delivered in TDM format. An interface document that describes the DSN local conventions for the TDM has recently been released [20], and the mapping between the DSN’s TRK-2-34 format and the TDM is very straightforward. Note that the TRK-2-34 format contains a lot of information that is very useful to DSN engineers in terms of troubleshooting and debugging problems in the DSN, however, much of this information is not particularly useful for navigation teams. The TRK-2-34 format is also network specific, which makes the TDM a better option for interagency tracking data exchanges.

Another future use of the TDM is in providing data for an eventual improvement in the ephemeris of Venus. In this endeavor, Delta-DOR measurements of ESA’s Venus Express spacecraft are being made on a monthly basis from ESA’s New Norcia and Cebreros tracking stations. The data are correlated at ESA/ESOC and provided to NASA/JPL in the TDM format in the same manner as was done for Phoenix. This effort also involves the interagency exchange of another CCSDS Navigation Working Group format, the Orbit Ephemeris Message (OEM) [4], to convey the ephemeris of the Venus Express orbiter.

Focus on the User

Transferring spacecraft tracking data in TDM format makes sense for international missions. Experiences with the prototyping of the TDM and the early implementations have shown that the international standard is relatively easy to code up and operate. As in both the examples cited here, individual agencies need not process the TDM directly in their orbit determination software. Rather, the agency user can use their existing tracking data formats internally, and develop software to convert between the international standard and their internal format. Using the interface in this manner enables each agency to easily exchange tracking between disparate resources, effectively extending the tracking networks of each agency. Code re-use is a very feasible option, as was illustrated with JPL’s Chandrayaan-1 implementation which was built upon the code base developed for the Phoenix mission ESA Delta-DOR data.

Using a standard such as the TDM will allow agencies to support tracking data exchange at lower cost, and on reduced implementation and checkout schedule. Because the TDM does not require the use of software developed by other agencies, the TDM can be implemented in any given space agency in any programming language they prefer, on any operating environment, independent of implementations in other agencies.

Summary / Conclusion

The early implementations of the CCSDS TDM lead to a few observations, including:

<u>OBSERVATION #1</u>: It is not necessary to implement the entire functionality of the TDM at once if there are mission constraints, time constraints, data type constraints, or budgetary constraints that must be accommodated. Agencies can re-use the TDM source code base if it needs to be extended for new data types and/or conventions.

<u>OBSERVATION #2</u>: It is not necessary for an agency to convert its internal tracking data processing to use the TDM. It is only necessary to implement reader/writer converters such that the data flow can be characterized as:

AgencyX format <=> TDM <=> AgencyY format

If specific constraints warrant, this exchange can be abbreviated even further, as in the case of the Phoenix Delta-DOR, for example:

AgencyX format => TDM => AgencyY format

<u>OBSERVATION #3</u>: Issues can arise in operational implementations, even though a prototyping process is dictated by the standards development process. However, it is likely the case that the incidence of specification errors is reduced given the existence of such a prototyping process. It is strongly recommended that any new or modified implementation is thoroughly tested before it is used in support of operational navigation.

<u>OBSERVATION #4</u>: Although the TDM is in principle “network generic”, there can be some effort required to understand the underlying data types being exchanged to ensure that the characterization in the TDM is understood well enough to correctly convert to the internal format. Such details may be incorporated into Interface Control Documents exchanged between the two agencies. The development of such documents should constitute part of the process of negotiating for tracking services.

Since its formal publication in November 2007, the TDM has seen limited use to date. It is hoped that the overall positive experiences of early TDM adopters described in this paper will help promote the use of the TDM in the future.

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Examples

```
CCSDS_TDM_VERS = 1.0
COMMENT Quasar CTD 20 also known as J023752.4+284808 (ICRF), 0234+285 (IERS)
CREATION_DATE = 2005-178T21:45:00
ORIGINATOR = NASA/JPL
META_START
TIME_SYSTEM = UTC
START_TIME = 2004-136T15:42:00.0000
STOP_TIME = 2004-136T16:02:00.0000
PARTICIPANT_1 = VOYAGER1
PARTICIPANT_2 = DSS-55
PARTICIPANT_3 = DSS-25
MODE = SINGLE_DIFF
PATH_1 = 1,2
PATH_2 = 1,3
TRANSMIT_BAND = X
RECEIVE_BAND = X
TIMETAG_REF = RECEIVE
RANGE_MODE = ONE_WAY
RANGE_MODULUS = 1.674852710000000E+02
RECEIVE_DELAY_3 = 0.000077
DATA_QUALITY = VALIDATED
META_STOP

DATA_START
COMMENT Timetag is time of signal arrival at PARTICIPANT_2.
COMMENT Transmit frequency is spacecraft beacon a OWLT before receive time.
DOR = 2004-136T15:42:00.0000 -4.911896106591159E-03
DOR = 2004-136T16:02:00.0000 1.467382930436399E-02
TRANSMIT_FREQ_1 = 2004-136T14:42:00.0000 8.415123456E+09
DATA_STOP

META_START
TIME_SYSTEM = UTC
START_TIME = 2004-136T15:52:00.0000
STOP_TIME = 2004-136T15:52:00.0000
PARTICIPANT_1 = CTD 20
PARTICIPANT_2 = DSS-55
PARTICIPANT_3 = DSS-25
MODE = SINGLE_DIFF
PATH_1 = 1,2
PATH_2 = 1,3
TRANSMIT_BAND = X
RECEIVE_BAND = X
TIMETAG_REF = RECEIVE
RANGE_MODE = ONE_WAY
RANGE_MODULUS = 1.674852710000000E+02
RECEIVE_DELAY_3 = 0.000077
DATA_QUALITY = VALIDATED
META_STOP

DATA_START
COMMENT Timetag is time of signal arrival at PARTICIPANT_2.
COMMENT Transmit frequency is reference for 2-station interferometer.
VLBI_DELAY = 2004-136T15:52:00.0000 -1.911896106591159E-03
TRANSMIT_FREQ_1 = 2004-136T15:42:00.0000 8.415123000E+09
DATA_STOP

META_START
TIME_SYSTEM = UTC
PARTICIPANT_1 = DSS-55
PARTICIPANT_2 = DSS-25
DATA_QUALITY = VALIDATED
META_STOP

DATA_START
CLOCK_BIAS = 2004-136T15:41:00.0000 -4.59e-7
DATA_STOP
```

Figure 1: TDM Example: Delta-DOR Observable

```
CCSDS_TDM_VERS=1.0
COMMENT TDM example created by yyyyy-nnnA Nav Team (NASA/JPL)
CREATION_DATE=2005-184T20:15:00
ORIGINATOR=NASA/JPL
META_START
TIME_SYSTEM=UTC
START_TIME=2005-184T11:12:23
STOP_TIME=2005-184T13:59:43.27
PARTICIPANT_1=DSS-55
PARTICIPANT_2=yyyy-nnnA
MODE=SEQUENTIAL
PATH=1,2,1
INTEGRATION_INTERVAL=1.0
INTEGRATION_REF=MIDDLE
FREQ_OFFSET=0.0
META_STOP
DATA_START
TRANSMIT_FREQ_1=2005-184T11:12:23     7175173383.615373
TRANSMIT_FREQ_RATE_1=2005-184T11:12:23  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:24     7175173384.017573
TRANSMIT_FREQ_RATE_1=2005-184T11:12:24  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:25     7175173384.419773
TRANSMIT_FREQ_RATE_1=2005-184T11:12:25  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:26     7175173384.821973
TRANSMIT_FREQ_RATE_1=2005-184T11:12:26  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:27     7175173385.224173
TRANSMIT_FREQ_RATE_1=2005-184T11:12:27  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:28     7175173385.626373
TRANSMIT_FREQ_RATE_1=2005-184T11:12:28  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:29     7175173386.028573
TRANSMIT_FREQ_RATE_1=2005-184T11:12:29  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:30     7175173386.430773
TRANSMIT_FREQ_RATE_1=2005-184T11:12:30  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:31     7175173386.832973
TRANSMIT_FREQ_RATE_1=2005-184T11:12:31  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:32     7175173387.235173
TRANSMIT_FREQ_RATE_1=2005-184T11:12:32  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:33     7175173387.637373
TRANSMIT_FREQ_RATE_1=2005-184T11:12:33  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:34     7175173388.039573
TRANSMIT_FREQ_RATE_1=2005-184T11:12:34  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:35     7175173388.441773
TRANSMIT_FREQ_RATE_1=2005-184T11:12:35  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:36     7175173388.843973
TRANSMIT_FREQ_RATE_1=2005-184T11:12:36  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:37     7175173389.246173
TRANSMIT_FREQ_RATE_1=2005-184T11:12:37  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:38     7175173389.648373
TRANSMIT_FREQ_RATE_1=2005-184T11:12:38  0.40220
TRANSMIT_FREQ_1=2005-184T11:12:39     7175173390.050573
RECEIVE_FREQ_1=2005-184T13:59:27.27  8429753135.986102
RECEIVE_FREQ_1=2005-184T13:59:28.27  8429749428.196568
RECEIVE_FREQ_1=2005-184T13:59:29.27  8429749427.584727
RECEIVE_FREQ_1=2005-184T13:59:30.27  8429749427.023103
RECEIVE_FREQ_1=2005-184T13:59:31.27  8429749426.346252
RECEIVE_FREQ_1=2005-184T13:59:32.27  8429749425.738658
RECEIVE_FREQ_1=2005-184T13:59:33.27  8429749425.113143
RECEIVE_FREQ_1=2005-184T13:59:34.27  8429749424.489933
RECEIVE_FREQ_1=2005-184T13:59:35.27  8429749423.876996
RECEIVE_FREQ_1=2005-184T13:59:36.27  8429749423.325228
RECEIVE_FREQ_1=2005-184T13:59:37.27  8429749422.664049
RECEIVE_FREQ_1=2005-184T13:59:38.27  8429749422.054996
RECEIVE_FREQ_1=2005-184T13:59:39.27  8429749421.425801
RECEIVE_FREQ_1=2005-184T13:59:40.27  8429749420.824186
RECEIVE_FREQ_1=2005-184T13:59:41.27  8429749420.204178
RECEIVE_FREQ_1=2005-184T13:59:42.27  8429749419.596043
RECEIVE_FREQ_1=2005-184T13:59:43.27  8429749418.986191
DATA_STOP
```

Figure 2: TDM Example: Two-Way Frequency Data for Doppler Observable Calculation

```
CCSDS_TDM_VERS = 1.0
   COMMENT TDM example created by yyyyy-nnnA Nav Team (NASA/JPL)
   CREATION_DATE = 2005-191T23:00:00
   ORIGINATOR = NASA/JPL
META_START
   COMMENT Range correction applied is range calibration to DSS-24.
   COMMENT Estimated RTLT at begin of pass = 950 seconds
   COMMENT Antenna Z-height correction 0.0545 km applied to uplink signal
   COMMENT Antenna Z-height correction 0.0189 km applied to downlink signal
   TIME_SYSTEM = UTC
   PARTICIPANT_1 = DSS-24
   PARTICIPANT_2 = yyyy-nnnA
   MODE = SEQUENTIAL
   PATH = 1,2,1
      INTEGRATION_REF = START
   RANGE_MODE = COHERENT
   RANGE_MODULUS = 2.0e+26
   RANGE_UNITS = RU
   TRANSMIT_DELAY_1 = 7.7e-5
   TRANSMIT_DELAY_2 = 0.0
   RECEIVE_DELAY_1  = 7.7e-5
   RECEIVE_DELAY_2  = 0.0
   CORRECTION_RANGE = 46.7741
   CORRECTIONS_APPLIED = YES
META_STOP
DATA_START
   TRANSMIT_FREQ_1      =  2005-191T00:31:51    7180064367.3536
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:31:51    0.59299
   RANGE                =  2005-191T00:31:51    39242998.5151986
   PR_N0                =  2005-191T00:31:51    28.52538
   TRANSMIT_FREQ_1      =  2005-191T00:34:48    7180064472.3146
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:34:48     0.59305
   RANGE                =  2005-191T00:34:48    61172265.3115234
   PR_N0                =  2005-191T00:34:48    28.39347
   TRANSMIT_FREQ_1      =  2005-191T00:37:45    7180064577.2756
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:37:45    0.59299
   RANGE                =  2005-191T00:37:45    15998108.8168328
   PR_N0                =  2005-191T00:37:45    28.16193
   TRANSMIT_FREQ_1      =  2005-191T00:40:42    7180064682.2366
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:40:42    0.59299
   RANGE                =  2005-191T00:40:42    37938284.4138008
   PR_N0                =  2005-191T00:40:42    29.44597
   TRANSMIT_FREQ_1      =  2005-191T00:43:39    7180064787.1976
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:43:39    0.60774
   RANGE                =  2005-191T00:43:39    59883968.0697146
   PR_N0                =  2005-191T00:43:39    27.44037
   TRANSMIT_FREQ_1      =  2005-191T00:46:36    7180064894.77345
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:46:36    0.60989
   RANGE                =  2005-191T00:46:36    14726355.3958799
   PR_N0                =  2005-191T00:46:36    27.30462
   TRANSMIT_FREQ_1      =  2005-191T00:49:33    7180065002.72044
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:49:33    0.60989
   RANGE                =  2005-191T00:49:33    36683224.3750253
   PR_N0                =  2005-191T00:49:33    28.32537
   TRANSMIT_FREQ_1      =  2005-191T00:52:30    7180065110.66743
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:52:30    0.60983
   RANGE                =  2005-191T00:52:30    58645699.4734682
   PR_N0                =  2005-191T00:52:30    29.06158
   TRANSMIT_FREQ_1      =  2005-191T00:55:27    7180065218.61442
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:49:33    0.60989
   RANGE                =  2005-191T00:55:27    13504948.3585422
   PR_N0                =  2005-191T00:55:27    27.29589
   TRANSMIT_FREQ_1      =  2005-191T00:58:24    7180065326.56141
   TRANSMIT_FREQ_RATE_1 =  2005-191T00:49:33    0.62085
   RANGE                =  2005-191T00:58:24    35478729.4012973
   PR_N0                =  2005-191T00:58:24    30.48199
   TRANSMIT_FREQ_1      =  2005-191T01:01:21    7180065436.45167
   RANGE                =  2005-191T01:01:21    57458219.0681689
   PR_N0                =  2005-191T01:01:21    27.15509
DATA_STOP
```

Figure 3: TDM Example: Two-Way Ranging Data Only

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NOTE: web site references were valid as of the time of writing this paper. There is no guarantee that these references will persist.

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