



Synchronous Navigation with the Micro-Modem

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1.0 Overview

Accurate positioning of an acoustic modem can be determined by precisely knowing the transmit and receive times of underwater acoustic communications packets, which provides time-of-flight information, and by transmitting the position of several other modems in the local acoustic network. This capability requires an accurate clock connection to all participating WHOI Micro-Modems, and the ability to deliver accurate absolute position and time in a single acoustic packet.

By providing a reference clock and modem positions, the user can calculate position within an acoustic network. This simple implementation relies on adding accurate transmit and receive timing to the Physical Layer, and allowing absolute position and time reporting in the Data Layer.

To enable clock-synchronous transmissions the Micro-Modem parameter setting SNV must be set to 1. To enable the time-of-arrival messages the parameter setting TOA must be set to 1.

1.1 Documentation

The latest version of this document and the hardware reference drawings listed below are available at:

<http://acomms.whoi.edu/>

2.0 Implementation Description

Accurate and precise time measurements are made by the Micro-Modem by using an external Pulse-Per-Second (PPS) signal along with the Micro-Modem's A/D converter sample clock. The accurate external PPS signal, along with an initializing NMEA serial string (CCCLK), provides absolute time with a 1-second resolution. The A/D sample clock provides precise sub-second timing between PPS rising edges, with a resolution of 12.5 microseconds. The data is processed after demodulation to 8 kHz sampled base-band, which results in a measurement resolution of 125 microseconds, or 18.75 cm using a sound speed of 1500 m/sec.

The absolute times of arrival of the received packets are reported relative to these clocks using the CATOA message, and data communications transmissions are synchronized to the PPS signal when the SNV setting is 1.

2.0.1 Hardware Interface

Board Designation	Interface	Reference
Micro-Modem 1.1B	JP4 Pin 1	WHOI Drawing 201001-ASM Rev. C
Micro-Modem 1.3	JP4 Pin 5	WHOI Drawing 201002-ASM Rev. A

Note: a slight modification to the Micro-Modem 1.1B DSP card is required to connect the signals to the right input on the modem. Boards with this modification have the designation "E7" on U33.

2.1 Clock Reference

The external clock reference for absolute time reporting by the Micro-Modem is a TTL PPS signal, as shown below, and an NMEA serial message (CCCLK) setting absolute time to the second. The modem will be able to report times of arrival with various feeds. See "Timing Modes" below. Important notes:

- a. The external PPS signal must be connected to pin 1 on JP4 of the Micro-Modem-1.1B main board. The signal must be greater than 2.4 Volts when active, and less than 0.6 Volts when not asserted. The absolute maximum voltage on this pin is +/-25 Volts. The polarity of the PPS signal is a rising edge at the start of each second.
- b. The CCCLK message must be sent to the modem each time it boots in order to set the time. A modem boot is indicated by the CAREV message with the INIT string. User software should monitor for this message and perform a clock synchronization sequence with the Micro-Modem when it is detected. To allow the Micro-Modem to first detect the PPS signal after boot, the CCCLK message must be sent 2 or more seconds after the CAREV INIT message is printed.
- c. If the Micro-Modem loses the PPS signal, for instance due to a cabling problem, this error is not immediately detected. Loss of PPS will be detected when: (1) PPS is lost, then recovered with at least one PPS rising edge missed; (2) PPS is lost, then a synchronous transmit is requested, by having the SNV state variable set to 1; (3) PPS is lost, and a packet detection occurs (regardless of the TOA state variable setting). In each of these cases, the Micro-Modem will determine that the PPS signal has been lost, and will respond with error messages as described below under Timing Modes.

2.1.1 Synchronization

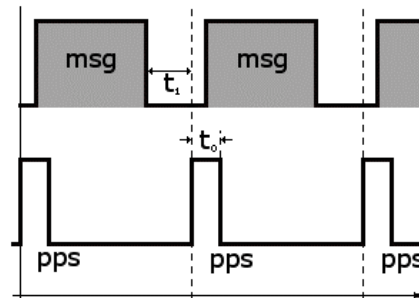
The diagram to the right shows the PPS and NMEA serial message clock reference signals. The two parameters t_0 and t_1 must fall within limits as follows:

$$t_0: t_0 \geq 1 \text{ milliseconds}$$

$$t_1: t_1 \geq 50 \text{ milliseconds}$$

Note: the specification on t_1 must be followed regardless of message length or baud rate.

Also note that although the timing diagram above has a serial message after each PPS rising edge, there is no requirement for this. A single CCCLK message is adequate to initialize the clock.



2.1.2 NMEA Clock Command

The user initializes the Micro-Modem's clock by issuing an NMEA clock message. As shown in the timing diagram above, the Micro-Modem receives the PPS rising edge at the start of a second, then receives the CCCLK message containing the time *for that same second* interval. Subsequent PPS rising edges increment the modem's time, synchronously with the external time reference. Between PPS rising edges, the A/D sample counter serves as the Micro-Modem's high-resolution timer.

CCCLK

Message from host to modem setting the clock, and synchronizing the A/D sample clock to the PPS signal if it exists.

\$CCCLK,YYYY,MM,DD,hh,mm,ss*CS

YYYY	Year
MM	Month
DD	Day
hh	hour
mm	minute
ss	second
*CS	Hex coded checksum (8 bit XOR of sentence)

Example: \$CCCLK,2004,10,28,16,20,00

Set the clock to October 28, 2004 16:20:00.

As an explanatory aside, the Micro-Modem has several clock sources. This document describes using the Micro-Modem's externally-referenced clock. (The Micro-Modem's externally-referenced clock is just a second counter, initialized by the CCCLK message, and incremented by the rising edge of the external PPS signal.) The Micro-Modem also has an onboard real-time clock (RTC). The CCCLK message will initialize both the RTC and the Micro-Modem's externally-referenced clock with the specified time.

If the Micro-Modem has detected an external PPS signal and has been initialized by the CCCLK message, it will be in Timing Mode 3 (see below). In Timing Mode 3, the Micro-Modem will report its externally-referenced clock in all messages with timestamps. In all other Timing Modes (0, 1, or 2), the Micro-Modem will report the time as kept by the RTC.

At the time of the CCCLK message, the RTC's time will be set to the time specified in the CCCLK message, which will be within 1 second of the external reference time. The RTC's crystal has an accuracy of 20ppm, and this frequency offset is temperature-dependent. The RTC does not use the external PPS signal, and so it may have both an offset and a drift relative to the externally-referenced clock.

2.2 Arrival Time Reporting

If the Time of Arrival messaging is enabled (NVRAM parameter TOA=1), the modem will report a time of arrival estimate for each acoustic packet. The estimate may or may not be synched. The user must inspect the timing mode field to determine the quality of time information.

2.2.1 NMEA Time of Arrival Message

Time of arrival of each acoustic packet will be reported with an NMEA message. The message is formatted as follows:

CATOA

Message from modem to host reporting time of arrival of the previous packet, and the synchronous timing mode used to determine that time.

\$CATOA,HHMMSS.SSSS,MODE*CS

HHMMSS.SSSS	Time of Arrival
MODE	Timing mode (see section 2.2.2 below)
*CS	Hex coded checksum (8 bit XOR of sentence)

Example: \$CATOA,134351.1250,3

At time 13:43:51.1250 the modem received a data packet. The timestamp was formed using Timing Mode 3 (see timing mode descriptions below).

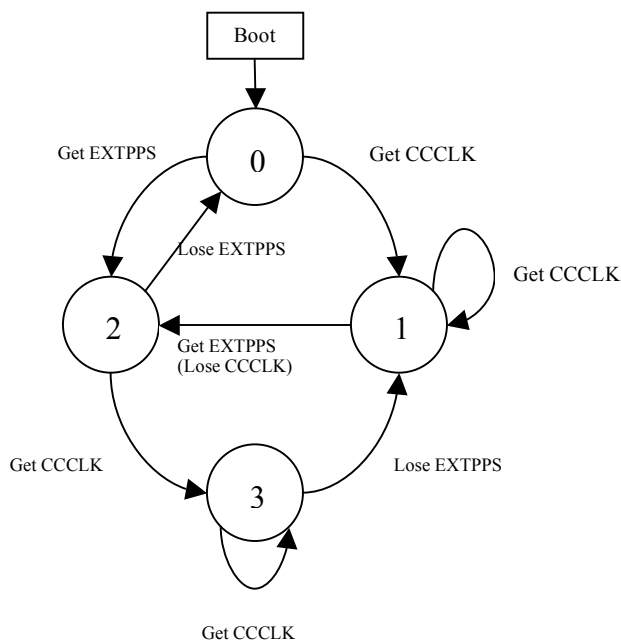
Note that in Timing Mode 2, the absolute time's hour-minute-second (**HHMMSS**) may be wrong, but the fractional second from the last rising edge of the PPS signal (**.SSSS**) will be correct.

2.2.2 Timing Modes

The modem reports a timing mode, representing how it is synched to the clock reference, as shown in the table on the right. This indicator provides synchronization success feedback to the user. The user must monitor mode to ensure that any system issues will be detected.

Timing mode	Synched to PPS	Initialized by CCCLK	Notes
0	No	No	a. Time was not set using CCCLK message, and b. No PPS is present, and therefore do not use.
1	No	Yes	a. Time was set using CCCLK message, and b. No PPS was present, therefore do not use.
2	Yes	No	a. A PPS signal is present, but b. Time was not set using CCCLK message, therefore the fractional seconds are correct, but the time is not. It is unlikely that this mode is useful in any real application.
3	Yes	Yes	a. A PPS signal is present, and b. Time was set using the CCCLK message, and therefore the time of arrival is good.

Timing Mode State transitions (for informational purposes only):



Loss of External PPS

A loss of the external PPS signal will be detected at the following times:

- 1.) If the external PPS signal was present, then is lost, and then returns after missing one or more rising edges, the Micro-Modem will detect this and change its timing mode as shown in the state transition diagram above. No error message will be printed.
- 2.) If the SNV state variable is set to 1 and a packet transmit is requested, the transmit will be synchronous with the next external PPS rising edge. If the external PPS signal is not present, the Micro-Modem will time out waiting for it, will not transmit, and will issue the error message "\$CAERR,EXTSYNC timeout on txput,0*CS", where CS is the NMEA checksum. (Note that when attempting to transmit a PSK packet, the error message will read "txpsk" instead of "txput".) The Micro-Modem will change its timing mode accordingly.
- 3.) Upon detection of a packet, if the external PPS signal has been lost, the Micro-Modem will detect this and change its timing mode accordingly. No error message will be printed. If the TOA state variable is set to 1, however, the CATOA message will display the updated timing mode, which will indicate loss of the external PPS signal.

2.2.3 \$CATOA Example

The table below shows NMEA message traffic from the Micromodem including the \$CATOA messaging. In this example, the \$CAREV "heart beat" message is seen, then the modem reports the \$CADQF and \$CATOA of the incoming Cycle Initialization mini-packet. The \$CACYC message announces the new cycle (in this case, Command is 1, SRC is 0, DST is 2, Packet Type is 0, ACK is 0, number of packets is 1). After the \$CACYC, the next message is the \$CADQF (quality of the received data) and \$CATOA of the data packet. The \$CARXD is the data contained in the packet. Finally the next \$CAREV "heart beat" message occurs. Note that the \$CAREV messages contain a timestamp and are 20 seconds apart.

It is important to note that this is the simplest example. Other message (e.g. \$CAMFD, \$CADOP or \$CASHF) may be requested by the user (depending on the level of verbosity required), and these messages would occur between the \$CADQF and the \$CATOA message. Note also, that the \$CATOA message is reporting mode 3; in this case the Micro-modem's local clock has been set, and the PPS signal is present.

Micro-Modem Message	Notes
\$CAREV,195405,AUVSN,0.90.0.32*18	Revision message "heart beat"
\$CADQF,250,2*54	A Cycle Init packet has been received (the 2 indicates that it is a Cycle-Init) and the quality of the packet is 250.
	Other messages may be sent from the modem to the user after the \$CADQF.
\$CATOA,195419.0066,3*4F	The time of arrival is 19:54:19.0066 (HH:MM:SS.SSSS). PPS mode is 3, Modem clock has been set and the PPS is present.
(short delay between packets)	
\$CACYC,1,0,2,0,0,1*59	The parameters of the Cycle-Init packet are: Mode 1 (data downlink), Unit 0 talks to Unit 2, etc.
\$CADQF,253,1*54	A data packet has been received (the 1 indicates that it is a data packet) and the quality of the packet is 253.
\$CATOA,195421.0066,3*4F	The time of arrival is 19:54:21.0066 (HH:MM:SS.SSSS). PPS mode is 3, Modem clock has been set and the PPS is present.
\$CARXD,0,2,0,1,00000 ...	The data associated with the packet is sent to the user. Unit 0 is source, unit 2 is destination.
\$CAREV,195425,AUVSN,0.90.0.32*18	Revision message. Note that it is 20 seconds after the previous one which means that CTO is set to 20.

2.3 Synchronous Transmission

Synchronous transmission allows sending acoustic packets right at a PPS signal instant so that the arrival time on a receiver with a synchronized clock can be used for one-way ranging. The synchronous transmit feature is enabled by setting the Micro-Modem Non-volatile RAM parameter SNV to 1. When set to one and the PPS signal is present the modem will wait for the upcoming PPS tick when transmitting data packets.

Error Condition: If no 1 PPS is present the Micro-Modem will time-out with an error: \$CAERR,TTTTTT,SNV_TIMEOUT. If this error occurs the transmission will not be sent. In order to continue with communications the SNV parameter must be set back to 0. This ensures that a problem with the 1 PPS signal will be detected by the host platform and that transmissions that were meant to be synchronized are not sent out when the clock is not present (which would result in bad fixed being received by navigation clients).

Timing constraints: The data to be transmitted must be provided to the modem prior to the second that it is to be sent. The Micro-Modem data request message CADRQ may not be deterministic time with respect to the 1 PPS input, but the timing constraint on the data message sent back to the Micro-Modem is simple:

- The data message must be received at least 50 msec prior to the 1 PPS transition that transmission is desired.

Thus the time in the MDAT_CNA message should be set by the user to the current time plus 1 second (and the navigation solution adjusted accordingly as well if necessary or possible) and the host computer may require the ability to keep time to at least 0.1 second accuracy with respect to the system PPS.

3.0 User Control

A Micro-Modem can provide ranging to Micro-Modem beacons, and the locations of those beacons to the user. The user must take care to configure all modems in the network properly, provide an accurate clock reference, and synchronize clocks often. The user must also provide the CCL frame described below, to provide a range and location pair to be used in generating a solution.

3.1 Modem Configuration

All modems navigating and providing range and location data should use the following recommended settings:

Setting	Value	Description
DTO	varies	Data timeout must be set to 1 minimum, but may be longer if the host computer requires more time to create the MDAT_CNA message to be transmitted.
NRV	150	Combine with CTO below – number of CTOs before modem reboots, printing CAREV INIT message, and thus requiring a new CCCLK to synch the clock.
CTO	10	A long enough cycle for extra delays associated with synchronous transmission
TXP	0	Disable transmitter-on messaging (recommended)
TXF	0	Disable transmitter-off messaging (recommended)
TOA	1	Enable Time of Arrival notifications (only required for receivers)
SNV	1	Enable synchronous transmit (only required for transmitters)

4.0 Data Layer Implementation

4.1 New CCL Data Frame

A new Compact Control Language (CCL) frame is needed to encode high resolution time and position. The data in this message refers to the time of packet transmission, and transmitter's transducer position estimated at some time. Thus the message should contain a high resolution latitude and longitude position fix, the time of that fix, and the time of the packet transmission.

4.1.1 New CCL Frame Definition

Messages can now be defined, to transfer data. Each message will be sized and typed, providing a fixed length context specific block, for transfer. The message definition is shown below:

```
/*
 * C-language structure for 32-byte AUV Compact Control Language Sentence:
 *
 * Note: structure elements are ordered to ease packing, not by importance.
 */
typedef struct
{ //
  unsigned char    mode;           // (1) Compact Ctrl Lang: MDAT_CNA
  unsigned char    type;           // (2) type of position fix
  unsigned char    heading;        // (3) 0-360 heading into 0-255
  unsigned char    est_speed;      // (4) 0-6.3m/s, 2.5cm/sec resolution
  unsigned short   depth;          // (6) resolution: depth-varying (3b unused)
  unsigned short   cep;            // (8) 0.1m resolution (4b unused)
  unsigned long    csound_gpsstd;  // (12) csound: 12 bits;gpsstd 10b ea
  float            latitude;       // (16) in float degrees, 4 bytes
  float            longitude;      // (20)
  unsigned long    time_of_ping;   // (24) tx on pulse-per-second tick
  unsigned long    time_of_fix;   // (28) to nearest second
  unsigned short   minutes_since_sync; // (30) up to 45 days
  unsigned short   gps_hdop_nsat; // (32) hdop: 12bits; nsat: 4 bits
} MODEM_MSG_DATA_CNA;
```

4.1.2 Message element definitions

mode: Compact Control Language (CCL) mode: MDAT_CNA

type: type of position fix:

Bits 0-1: fix method:

00	GPS fix
01	Inertial reckoning
10	Acoustic fix
11	Dead reckoning

Bits 2-3: fix mode

if GPS:

00	generic, e.g. not differential, not WAAS
01	Differential
02	WAAS enabled

if inertial: 00 No special information available

if acoustic: *Not yet defined*

if dead-reckoning: *Not yet defined*

Bits 4-5: platform motion:

00	Fixed
01	Moored
10	Mobile
11	reserved

Bits 6-7: reserved (set to 00)

heading: use CCL Encode_heading()/Decode_heading()
Range 0-360 degrees, resolution 1.4 degrees

est_speed: use CCL Encode_velocity()/Decode_velocity()
Range 0-6.375 m/s, resolution 2.5cm/s

depth: use CCL Encode_depth()/Decode_depth()
Range 0-6000m, resolution: (only uses 13 bits...)

0- 100m:	0.1m
100- 200m:	0.2m
200-1000m:	0.5m
1000-6000m:	1.0m

cep: Circular Error Probable, radius. Range: 0-6.55km, 0.1m resolution.

Special values:

0.0m: CEP is not reported.

6553.5m: CEP is \geq 6553.5m. (or use 409.5m etc)

csound_gpsstd: Encoded Speed of Sound and GPS Standard Deviations

Bits 0-11: (speed_of_sound-1425m/s)/(5cm/s): 12 bits.

Bits 12-21: GPS latitude standard deviation, 0.1m resolution,

Range: 0.1m-102.2m

Special values: 0.0m: not reported, or not GPS mode

102.3m: std \geq 102.3m

Bits 22-31: GPS longitude standard deviation, 0.1m resolution,

Range: 0.1m-102.2m

Special values: 0.0m: not reported, or not GPS mode

102.3m: std \geq 102.3m

lat/lon: 32-bit floats. Need precision $<$ 0.1m.

time_of_ping: seconds since 1970.

time_of_fix: seconds since 1970.

minutes_since_sync: minutes since last GPS sync. Counts up to about 45 days.

Special values: 0: not reported

65535: \geq 65535 minutes (about 45 days)

gps_hdop_nsat: Encoded GPS HDOP (Horizontal Dilution of Precision) and GPS Number of Satellites.

If type is not GPS, set to 0.

Bits 0-11: HDOP, 0.1m-409.5m, resolution 0.1m.

Special values: 0.0m: not reported

409.5m: HDOP is \geq 409.5m

Bits 12-15: NSAT: number of satellites in fix, 1-15.

Special values: 0: NSAT not reported.

5.0 Performance

The performance of the system was tested on the bench using a Garmin GPS-16 and ModemTool-3.17. ModemTool 3.17 includes the capability to monitor the GPS signal and provide the CCCLK messages to the modem. The PPS signal was provided to both Micro-Modems, which had their respective analog inputs and outputs directly connected.

5.1 Transmission Synchronization Accuracy

The transmit jitter was measured on an oscilloscope by monitoring the 1 PPS signal and the outgoing waveform. The jitter was typically +/- 5 microseconds, and up to +/- 10 microseconds at most. This corresponds to a range jitter of approximately 2 cm at the transmitter.

5.1 Receiver Accuracy

Results from a test with 1400 trials were collected:

- Offset: measured to be 500 microseconds (on a wire this should be zero). The offset will be calibrated to zero in the firmware.
- Jitter: 98.1% are within +/- 1 baseband sample (125 microseconds).
- Outliers: less than 2 percent fall between 500 micro-seconds offset and 0.

6.0 Summary

The WHOI Micro-Modem can make synchronized transmissions which can provide one-way travel times and transmitter locations to a moving modem, in the acoustic network footprint. By connecting a suitable clock reference, configuring the modem properly, synchronizing the modem clock, and transmitting time and location data, the user can make one-way travel time based receiver position estimates.

7.0 Document Revision History

[unnamed revision], 26 Nov 2004: First Draft of Specification

Revision A, 22 Dec 2004: Second Draft of Specification. Various updates, in particular on Timing Modes.

Revision B, 6 Jan 2004: Added initial results.

Revision C, Unspecified minor changes

Revision D, 30 Mar 2005: Added example of TOA NMEA strings and hardware information.