# U4BProtocol Specification

# w/references to WsprEncoded C/Python Libraries

Current versions

U4BProtocol Specification v1.1

WsprEncoded Library v4.3.2

**Table of Contents**

[U4BProtocol &WsprEncoded C/Python Libraries Specification 1](#__RefHeading___Toc2111_1057631513)

[Intent 4](#__RefHeading___Toc2113_1057631513)

[Updates 5](#__RefHeading___Toc2115_1057631513)

[History 5](#__RefHeading___Toc2117_1057631513)

[License 5](#__RefHeading___Toc2119_1057631513)

[Basic Telemetry 6](#__RefHeading___Toc2121_1057631513)

[Overview 6](#__RefHeading___Toc2123_1057631513)

[Message Format 6](#__RefHeading___Toc2125_1057631513)

[Telemetry Fields 7](#__RefHeading___Toc2127_1057631513)

[Field Specifications 7](#__RefHeading___Toc2129_1057631513)

[Grid Position Enhancement (Grid5 & Grid6) 7](#__RefHeading___Toc2131_1057631513)

[Purpose 7](#__RefHeading___Toc2133_1057631513)

[Resolution Improvement 7](#__RefHeading___Toc2135_1057631513)

[Encoding 7](#__RefHeading___Toc2137_1057631513)

[Example 7](#__RefHeading___Toc2139_1057631513)

[Altitude Measurement 7](#__RefHeading___Toc2141_1057631513)

[Specification 7](#__RefHeading___Toc2143_1057631513)

[Usage 8](#__RefHeading___Toc2145_1057631513)

[Temperature Measurement 8](#__RefHeading___Toc2147_1057631513)

[Specification 8](#__RefHeading___Toc2149_1057631513)

[Rollover Behavior 8](#__RefHeading___Toc2151_1057631513)

[Rollover Example 8](#__RefHeading___Toc2153_1057631513)

[Voltage Measurement 8](#__RefHeading___Toc2155_1057631513)

[Specification 8](#__RefHeading___Toc2157_1057631513)

[Standard Rollover Ranges 9](#__RefHeading___Toc2159_1057631513)

[Encoding 9](#__RefHeading___Toc2161_1057631513)

[Alternative Encoding example for only 3.0 to 4.95v with clamping 9](#__RefHeading___Toc2163_1057631513)

[Decoding voltage assuming it represents 3.0 to 4.95v range at original measurement 9](#__RefHeading___Toc2165_1057631513)

[Speed Measurement 9](#__RefHeading___Toc2167_1057631513)

[Specification 9](#__RefHeading___Toc2169_1057631513)

[Usage 10](#__RefHeading___Toc2171_1057631513)

[GPS Validity Flag 10](#__RefHeading___Toc2173_1057631513)

[Purpose 10](#__RefHeading___Toc2175_1057631513)

[Values 10](#__RefHeading___Toc2177_1057631513)

[Usage 10](#__RefHeading___Toc2179_1057631513)

[Telemetry Type Header 10](#__RefHeading___Toc2181_1057631513)

[Purpose 10](#__RefHeading___Toc2183_1057631513)

[Values 10](#__RefHeading___Toc2185_1057631513)

[Usage 10](#__RefHeading___Toc2187_1057631513)

[Encoding examples 10](#__RefHeading___Toc2189_1057631513)

[encodeBasicTelemetry() 10](#__RefHeading___Toc2191_1057631513)

[decodeBasicTelemetry() 11](#__RefHeading___Toc2193_1057631513)

[Complete Example 11](#__RefHeading___Toc2195_1057631513)

[Encoding Architecture 12](#__RefHeading___Toc2197_1057631513)

[Two-Stage Encoding Process 12](#__RefHeading___Toc2199_1057631513)

[Stage 1: Callsign Encoding 12](#__RefHeading___Toc2201_1057631513)

[Stage 2: Grid+Power Encoding 12](#__RefHeading___Toc2203_1057631513)

[Rollover Considerations 12](#__RefHeading___Toc2205_1057631513)

[Advantages 12](#__RefHeading___Toc2207_1057631513)

[Disadvantages 12](#__RefHeading___Toc2209_1057631513)

[Best Practices 12](#__RefHeading___Toc2211_1057631513)

[Implementation-Specific Behavior 13](#__RefHeading___Toc2213_1057631513)

[Example: 13](#__RefHeading___Toc2215_1057631513)

[Voltage Range Restriction 13](#__RefHeading___Toc2217_1057631513)

[Behavior Differences 13](#__RefHeading___Toc2219_1057631513)

[Transmission Scheduling 13](#__RefHeading___Toc2221_1057631513)

[Channel Selection 13](#__RefHeading___Toc2223_1057631513)

[Integration with Channel Map 14](#__RefHeading___Toc2225_1057631513)

[Error Handling 14](#__RefHeading___Toc2227_1057631513)

[Validation Functions 14](#__RefHeading___Toc2229_1057631513)

[Error Codes 14](#__RefHeading___Toc2231_1057631513)

[Performance Characteristics 15](#__RefHeading___Toc2233_1057631513)

[Encoding Efficiency 15](#__RefHeading___Toc2235_1057631513)

[Precision Trade-offs 15](#__RefHeading___Toc2237_1057631513)

[ChannelMap Specification 15](#__RefHeading___Toc2239_1057631513)

[Overview 15](#__RefHeading___Toc2241_1057631513)

[Core Concepts 15](#__RefHeading___Toc2243_1057631513)

[Message Types 15](#__RefHeading___Toc2245_1057631513)

[Channel Identification 15](#__RefHeading___Toc2247_1057631513)

[Data Structures 15](#__RefHeading___Toc2249_1057631513)

[Channel Object 15](#__RefHeading___Toc2251_1057631513)

[Telemetry Message Structure 16](#__RefHeading___Toc2253_1057631513)

[Identification Methods 16](#__RefHeading___Toc2255_1057631513)

[1. ID13 Encoding 16](#__RefHeading___Toc2257_1057631513)

[Example 16](#__RefHeading___Toc2259_1057631513)

[2. Time Slot Identification 16](#__RefHeading___Toc2261_1057631513)

[3. Frequency Matching 16](#__RefHeading___Toc2263_1057631513)

[Target Frequency 16](#__RefHeading___Toc2265_1057631513)

[Frequency Fingerprinting, Frequency binning or other mechanisms 16](#__RefHeading___Toc2267_1057631513)

[Implementation Notes 17](#__RefHeading___Toc2269_1057631513)

[Receiver Calibration Challenges 17](#__RefHeading___Toc2271_1057631513)

[Fingerprinting Algorithm 17](#__RefHeading___Toc2273_1057631513)

[Performance Considerations 17](#__RefHeading___Toc2275_1057631513)

[Channel Map Integration 17](#__RefHeading___Toc2277_1057631513)

[Extended Telemetry Specification 18](#__RefHeading___Toc2279_1057631513)

[Overview 18](#__RefHeading___Toc2281_1057631513)

[Key Features 18](#__RefHeading___Toc2283_1057631513)

[Message Architecture 18](#__RefHeading___Toc2285_1057631513)

[Message Structure 18](#__RefHeading___Toc2287_1057631513)

[Header Fields 18](#__RefHeading___Toc2289_1057631513)

[Header Field Details 18](#__RefHeading___Toc2291_1057631513)

[Message Types 19](#__RefHeading___Toc2293_1057631513)

[Planned Enumerated Types (Examples) 19](#__RefHeading___Toc2295_1057631513)

[Time Slot Management 19](#__RefHeading___Toc2297_1057631513)

[10-Minute Window Structure 19](#__RefHeading___Toc2299_1057631513)

[Transmission Patterns 19](#__RefHeading___Toc2301_1057631513)

[Backward Compatible 19](#__RefHeading___Toc2303_1057631513)

[Extended Only 20](#__RefHeading___Toc2305_1057631513)

[Mixed Mode 20](#__RefHeading___Toc2307_1057631513)

[Encoding Specification 20](#__RefHeading___Toc2309_1057631513)

[Data Encoding 20](#__RefHeading___Toc2311_1057631513)

[Packing Order 20](#__RefHeading___Toc2313_1057631513)

[Value Processing 20](#__RefHeading___Toc2315_1057631513)

[Example Implementation 20](#__RefHeading___Toc2317_1057631513)

[GPS Stats Message (Hypothetical) 20](#__RefHeading___Toc2319_1057631513)

[Packing Example 21](#__RefHeading___Toc2321_1057631513)

[Integration Guidelines 21](#__RefHeading___Toc2323_1057631513)

[Receiver Implementation 21](#__RefHeading___Toc2325_1057631513)

[Sender Implementation 21](#__RefHeading___Toc2327_1057631513)

[Fingerprinting Logic 21](#__RefHeading___Toc2329_1057631513)

[Error Handling 21](#__RefHeading___Toc2331_1057631513)

[Invalid Messages 21](#__RefHeading___Toc2333_1057631513)

[Backward Compatibility 22](#__RefHeading___Toc2335_1057631513)

[Future Extensions 22](#__RefHeading___Toc2337_1057631513)

[WsprEncoded C++ Library 22](#__RefHeading___Toc2339_1057631513)

[Overview 22](#__RefHeading___Toc2341_1057631513)

[Features 22](#__RefHeading___Toc2343_1057631513)

[Core Capabilities 22](#__RefHeading___Toc2345_1057631513)

[Design Principles 22](#__RefHeading___Toc2347_1057631513)

[Installation 23](#__RefHeading___Toc2349_1057631513)

[Arduino Library Manager 23](#__RefHeading___Toc2351_1057631513)

[CMake Integration 23](#__RefHeading___Toc2353_1057631513)

[Option 1: FetchContent (Recommended) 23](#__RefHeading___Toc2355_1057631513)

[Option 2: Git Submodules 23](#__RefHeading___Toc2357_1057631513)

[Option 3: External Directory 23](#__RefHeading___Toc2359_1057631513)

[API Reference 23](#__RefHeading___Toc2361_1057631513)

[Core Headers 23](#__RefHeading___Toc2363_1057631513)

[Basic Telemetry API 23](#__RefHeading___Toc2365_1057631513)

[Common Measurement Types 23](#__RefHeading___Toc2367_1057631513)

[Encoding Functions 24](#__RefHeading___Toc2369_1057631513)

[Usage Example 24](#__RefHeading___Toc2371_1057631513)

[Extended Telemetry API 25](#__RefHeading___Toc2373_1057631513)

[Custom Field Definition 25](#__RefHeading___Toc2375_1057631513)

[Custom Telemetry Example 25](#__RefHeading___Toc2377_1057631513)

[Channel Map API 26](#__RefHeading___Toc2379_1057631513)

[Channel Information 26](#__RefHeading___Toc2381_1057631513)

[Channel Map Example 26](#__RefHeading___Toc2383_1057631513)

[Complete Integration Example 27](#__RefHeading___Toc2385_1057631513)

[Arduino Tracker Implementation 27](#__RefHeading___Toc2387_1057631513)

[Desktop Application Integration 27](#__RefHeading___Toc2389_1057631513)

[Error Handling 28](#__RefHeading___Toc2391_1057631513)

[Common Error Codes 28](#__RefHeading___Toc2393_1057631513)

[Best Practices 28](#__RefHeading___Toc2395_1057631513)

[Performance Notes 29](#__RefHeading___Toc2397_1057631513)

[Memory Usage 29](#__RefHeading___Toc2399_1057631513)

[Processing Speed 29](#__RefHeading___Toc2401_1057631513)

[Platform Support 29](#__RefHeading___Toc2403_1057631513)

[Tested Platforms 29](#__RefHeading___Toc2405_1057631513)

[Compiler Requirements 29](#__RefHeading___Toc2407_1057631513)

# Intent

QRPLabs for some time has sold a tracker <https://www.qrp-labs.com/u4b.html> that has a behavior for transmitting WSPR packets to convey information from a balloon in flight over planet Earth. This info is received by worldwide WSPR receivers, and the data uploaded to accessible databases like wsprlive and wsprnet.

A number of trackers have been produced, some open-source and available on github.com that have behavior compatible with the QRPLabs U4B “protocol”. Additionally, websites have been created, or other software, that interprets the WSPR data and creates various analysis or visualizations.

The behavior of this protocol has changed over time, and various software may or may not support what is considered the “current definition”. That is fine. There is a discussion process at <https://groups.io/g/picoballoon> that attempts to keep all interested parties in alignment over time, with the benefit of shared software or website use, and to avoid conflict..i.e. one person’s tracker garbling correct reception of information from another person’s tracker.

QRPLabs has graciously allowed this compatible reverse-engineering. Hans G0UPL, over time, has released details of the U4B behaviors, which can be considered “U4B Protocol”.

QRPLabs is under no agreement to comply in the future with anything here, and this spec does not cover all behaviors of a QRPLabs U4B tracker.

The goal is to serve a common interest for all people in the u4b or u4b-compatible world, and create more fun!

Part of the fun is innovation. Change over time should be slow to minimize chaos in the U4B-compatible world, but hopefully it continues to happen. Important changes will be highlighted in the Updates section.

Some specification detail available on [https://www.qrp-labs.com](https://www.qrp-labs.com/) may be out of date and not reflect the true current behavior of U4B trackers.

This spec should be considered the current community consensus. Issues or Discussion can be posted at

https://github.com/traquito/WsprEncoded

<https://github.com/traquito/WsprEncodedPython>  
  
The intent is easy understanding by non-English speakers. It may take some time to get to a good spec, so revisions may happen more quickly during 2025.

# Updates

V1.1 Initial release at the current repo: [https://github.com/knormoyle/U4BProtocol](https://github.com/knormoyle/WsprEncoded)

# History

U3B and U3S WSPR on balloons appeared around 2015, with U4B development after that by Hans G0UPL and Dave VE3KCL.

Some other trackers reverse-engineered U4B protocol, but Doug KD2KDD did extensive work in that area starting in 2023. This was called the Traquito project.

Doug KD2KDD organized a collaborative effort to extend U4B protocol in 12/24 and made the extensions (Extended Telemetry) available under AGPL.

The original U4B protocol before 12/24 is considered to be Basic Telemetry. The extensions are considered to be Extended Telemery. Hans G0UPL aligned QRPLabs U4B firmware to the Extended Telemetry spec around 7/25.

The supporting library and clarity of definition here, are all because of Doug’s work, and the community thanks him for his time and commitment to the idea.

# License

This specification and the WsprEncoded library is under AGPL license.

This document provides specification for Basic and Extended U4B protocol, definition of channels to isolate telemetry from different transmitters, and a description of the WsprEncoded library available at<https://github.com/traquito/WsprEncoded>to simplify implementation of the protocol.

Contributions, modifications and extensions are encouraged and merges will be accepted via <https://github.com/knormoyle/U4BProtocol> repo.

U4BProtocol includes Basic Telemetry and Extended Telemetry. QRPLabs has some alternative transmissions with its legacy TELE instruction that are not part of this spec. The QRPLabs TELEX command meets the Extended Telemetry spec.

# Basic Telemetry

## Overview

The Basic Telemetry API provides a standardized method for encoding common tracker measurements into WSPR Type 1 messages. This system enables transmission of GPS location, environmental sensors, and system status information through the WSPR protocol's 50-bit data capacity.

Note that there can be bad GPS data on altitude, latitude and longitude, and voltage measurement can be bad also.

For example, if the tracker is not getting 3.3v to an rp2040 and rp2040 voltage measurement is only "right" if supply voltage to the rp2040 and the temperature ADC is getting a correct 3.3v compare voltage. A tracker may implement additional filtering or clamping to deal with those issues.

The language below governs what result happens on a website if no such filtering happens, i.e. what values are reported from particular encoded values.

Note there is no such thing as Nan or Invalid encodings. So it’s important to understand that Basic Telemetry will always decode to something. You always get an answer. The validity of that answer depends on an understanding of all of U4B Protocol.

Decoding of random unused callsign space spots from wsprlive will show that everything can decode to something (even it's out of the valid range of the intermediate "big number" for U4B protocol, if there is no checking for that).

The current basic telemetry doesn't fully occupy the space allowed by the wspr big-number encoding process. So just being able to decode something doesn’t validate that it’s U4B Protocol information.

It’s possible that unused big number space could be used for "anything" like NaN or None. Place holder for the future.

A common case is accidentally decoding WB8ELK protocol telemetry. It will sometimes have a intermediate big number range that’s illegal relative to U4B protocol telemetry. A website could detect that. It can be discovered by looking at the big number being out-of-expected-range, or having a remainder left over after decoding all known U4B protocol subfields from the big number.

## Message Format

Basic Telemetry messages use the WSPR Type 1 format with specific field allocations:

<callsign> <grid> <power>

**Field Mapping:**

* **Callsign**: Encodes Grid5, Grid6, and Altitude
* **Grid**: Encodes Temperature, Voltage, Speed, GPS validity, and telemetry type
* **Power**: Part of the encoding scheme

## Telemetry Fields

### Field Specifications

| Field Name | Unit | Min Value | Max Value | Step Size | Possible Values |
| --- | --- | --- | --- | --- | --- |
| Grid5 | Character | 0 | 23 | 1 | 24 |
| Grid6 | Character | 0 | 23 | 1 | 24 |
| Altitude | Meters | 0 | 21,340 | 20 | 1,068 |
| Temperature | Celsius | -50 | 39 | 1 | 90 |
| Voltage | Volts | 2.0 | 3.95 | 0.05 | 40 |
| Speed | Knots | 0 | 82 | 2 | 42 |
| IsGpsValid | Boolean | 0 | 1 | 1 | 2 |
| HdrTelemetryType | Enum | 0 | 1 | 1 | 2 |

### Grid Position Enhancement (Grid5 & Grid6)

#### Purpose

Extends the 4-character WSPR grid to 6 characters for improved location precision.

#### Resolution Improvement

* **4-character grid**: 70 × 140 miles resolution
* **6-character grid**: 3 × 3 miles resolution

#### Encoding

// Grid5 and Grid6 encode characters A-X (values 0-23)

char grid5\_char = 'A' + grid5\_value; // grid5\_value: 0-23

char grid6\_char = 'A' + grid6\_value; // grid6\_value: 0-23

// Complete 6-character grid formation

std::string full\_grid = wspr\_grid\_4char + grid5\_char + grid6\_char;

#### Example

// WSPR Type 1 grid: "FN31"

// Grid5 = 12 (M), Grid6 = 7 (H)

// Complete grid: "FN31MH"

### Altitude Measurement

#### Specification

* **Source**: GPS-derived elevation
* **Range**: 0 to 21,340 meters
* **Resolution**: 20-meter steps
* **Encoding**: Linear quantization with rollover support

#### Usage

uint16\_t encodeAltitude(uint16\_t altitude\_meters) {

// Rollover at 21340m.

// Trackers may optionally clamp to min/max range

// Negative numbers should also be filtered, in case of bad gps data

altitude\_meters = altitude\_meters % 21340;

// Quantize to 20m steps

return altitude\_meters / 20;

}

uint16\_t decodeAltitude(uint16\_t encoded\_value) {

return encoded\_value \* 20; // Convert back to meters

}

### Temperature Measurement

#### Specification

* **Source**: Environmental sensor or onboard temperature sensor
* **Range**: -50°C to +39°C
* **Resolution**: 1°C steps
* **Encoding**: Offset binary with rollover

#### Rollover Behavior

int16\_t encodeTemperature(int16\_t temp\_celsius) {

// Apply offset and rollover.

// Trackers should filter for negative results and do something (clamp?)

return (temp\_celsius - (-50)) % 90;

}

int16\_t decodeTemperature(uint16\_t encoded\_value) {

// Note: Rollover means ambiguous decoding

return encoded\_value + (-50);

}

#### Rollover Example

// Both -45°C and +45°C encode to the same value (5)

int16\_t temp1 = -45; // encodes to: (-45 - (-50)) % 90 = 5

int16\_t temp2 = 45; // encodes to: (45 - (-50)) % 90 = 5

### Voltage Measurement

#### Specification

* **Source**: System input voltage monitoring
* **Range**: 3.0 to 4.95v is considered the standard range, although a tracker can do continual wraparound, so there is no range limits, or pick a different 1.95v range
* **Resolution**: 0.05V steps
* **Purpose**: Monitor solar panel or battery performance

#### Standard Rollover Ranges

The voltage field can support multiple 1.95V ranges. There is no standard for how to decide what range a tracker is using though. 3.0 to 4.95v is considered the standard range. A tracker may clamp to min/max values for the range or not. Website viewers typically do not have a way of visualizing voltages correctly outside of the 3.0v to 4.95v range.

It's possible website developers could have a configurable "base voltage" so that balloons with different known voltage ranges could be supported and visualized easily. But 3-4.95v is the consensus, non-configurable range that websites should report.

Possible examples:

* 2.0V to 3.95V
* 4.0V to 5.95V
* 6.0V to 7.95V

#### Encoding

uint16\_t encodeVoltage(float voltage) {

uint16\_t range = (uint16\_t)((voltage - 2.0) / 2.0);

float range\_offset = voltage - (2.0 + range \* 2.0);

// Quantize within range

uint16\_t step = (uint16\_t)(range\_offset / 0.05);

return step % 40; // Rollover within 40 possible values

}

#### Alternative Encoding example for only 3.0 to 4.95v with clamping

uint16\_t encodeVoltage(float voltage) {

// voltage encodings:

// 20 to 39, 0 to 19 for 3.00 to 4.95V with a resolution of 0.05V

// 0 to 39 encodings

if (voltage > 4.95) voltage = 4.95;

else if (voltage < 3.00) voltage = 3.00;

// should only be 3 to 4.95

uint16\_t voltageNum = (int)(round ((voltage - 3.00) / .05) + 20) % 40;

return voltageNum

}

#### Decoding voltage assuming it represents 3.0 to 4.95v range at original measurement

uint16\_t decodedVoltage(float encoded\_value) {

voltage = round((encoded\_value \* 0.05) + 2.00, 2)

return voltage

}

### Speed Measurement

#### Specification

* **Source**: GPS-derived ground speed
* **Range**: 0 to 82 knots
* **Resolution**: 2-knot steps
* **Encoding**: Linear quantization with rollover

#### Usage

uint16\_t encodeSpeed(uint16\_t speed\_knots) {

return (speed\_knots / 2) % 42; // Rollover support

}

uint16\_t decodeSpeed(uint16\_t encoded\_value) {

return encoded\_value \* 2; // Convert back to knots

}

### GPS Validity Flag

#### Purpose

Indicates whether GPS-derived measurements (altitude, speed, grid position) are valid. Some trackers may only send callsign+telemetry when GPS is valid, so this may always be 1. QRPLabs u4b can send callsign+telemetry when GPS is not valid. Old values are used for telemetry then, although it’s possible some data should be ignored if GPS is not valid.

#### Values

* **0 (false)**: GPS lock not available, position/speed data invalid
* **1 (true)**: GPS lock acquired, position/speed data valid

#### Usage

bool gps\_valid = hasGpsLock();

uint8\_t gps\_flag = gps\_valid ? 1 : 0;

### Telemetry Type Header

#### Purpose

Identifies the telemetry format version.

#### Values

* **0**: Reserved
* **1**: Standard Basic Telemetry format

#### Usage

const uint8\_t TELEMETRY\_TYPE\_STANDARD = 1;

## Encoding examples

#### encodeBasicTelemetry()

Encodes all basic telemetry fields into a WSPR message.

struct BasicTelemetryData {

uint8\_t grid5; // 0-23

uint8\_t grid6; // 0-23

uint16\_t altitude\_meters; // 0-21340

int16\_t temperature\_c; // -50 to 39

float voltage\_v; // 2.0-3.95 (or rollover ranges)

uint16\_t speed\_knots; // 0-82

bool gps\_valid; // true/false

uint8\_t telemetry\_type; // 1 for standard

};

bool encodeBasicTelemetry(

const BasicTelemetryData& data,

WSPRMessage& message

);

#### decodeBasicTelemetry()

Decodes basic telemetry from a WSPR message.

bool decodeBasicTelemetry(

const WSPRMessage& message,

BasicTelemetryData& data

);

### Complete Example

#include <WsprEncoded/BasicTelemetry.h>

void transmitBasicTelemetry() {

// Collect sensor data

BasicTelemetryData telemetry = {

.grid5 = 12, // 'M'

.grid6 = 7, // 'H'

.altitude\_meters = 1200,

.temperature\_c = 25,

.voltage\_v = 3.7,

.speed\_knots = 0,

.gps\_valid = true,

.telemetry\_type = 1

};

// Encode to WSPR message

WSPRMessage message;

if (encodeBasicTelemetry(telemetry, message)) {

// Transmit WSPR message

printf("Transmitting: %s %s %d\n",

message.callsign, message.grid, message.power);

// Send via radio...

transmitWSPR(message);

}

}

void receiveBasicTelemetry(const WSPRMessage& received) {

BasicTelemetryData telemetry;

if (decodeBasicTelemetry(received, telemetry)) {

printf("Decoded telemetry:\n");

printf(" Location: %c%c extension\n",

'A' + telemetry.grid5, 'A' + telemetry.grid6);

printf(" Altitude: %d meters\n", telemetry.altitude\_meters);

printf(" Temperature: %d°C\n", telemetry.temperature\_c);

printf(" Voltage: %.2fV\n", telemetry.voltage\_v);

printf(" Speed: %d knots\n", telemetry.speed\_knots);

printf(" GPS Valid: %s\n", telemetry.gps\_valid ? "Yes" : "No");

}

}

## Encoding Architecture

### Two-Stage Encoding Process

Basic Telemetry uses a two-stage encoding process to fit all fields into WSPR message components:

#### Stage 1: Callsign Encoding

// Encode Grid5, Grid6, and Altitude into callsign

BigNumber callsign\_data = 0;

callsign\_data = callsign\_data \* 24 + grid5;

callsign\_data = callsign\_data \* 24 + grid6;

callsign\_data = callsign\_data \* 1068 + altitude\_index;

#### Stage 2: Grid+Power Encoding

// Encode remaining fields into grid and power

BigNumber grid\_power\_data = 0;

grid\_power\_data = grid\_power\_data \* 90 + temperature\_index;

grid\_power\_data = grid\_power\_data \* 40 + voltage\_index;

grid\_power\_data = grid\_power\_data \* 42 + speed\_index;

grid\_power\_data = grid\_power\_data \* 2 + gps\_valid;

grid\_power\_data = grid\_power\_data \* 2 + telemetry\_type;

### Rollover Considerations

#### Advantages

* Measurements not strictly limited to defined ranges
* Handles sensor readings outside nominal ranges
* Continuous operation during extreme conditions

#### Disadvantages

* **Ambiguous decoding**: Multiple input values map to same encoded value
* **Requires context**: Additional information needed for correct interpretation
* **Data loss**: Precision lost due to quantization and rollover

#### Best Practices

// Implement bounds checking before encoding

float clampVoltage(float voltage, float min\_v, float max\_v) {

if (voltage < min\_v) return min\_v;

if (voltage > max\_v) return max\_v;

return voltage;

}

// Use application-specific knowledge for decoding

int16\_t decodeTemperatureWithContext(uint16\_t encoded, int16\_t expected\_range) {

int16\_t base\_temp = encoded - 50;

// Apply context-based correction

while (abs(base\_temp - expected\_range) > 45) {

if (base\_temp < expected\_range) {

base\_temp += 90; // Next rollover range

} else {

base\_temp -= 90; // Previous rollover range

}

}

return base\_temp;

}

## Implementation-Specific Behavior

#### Example:

* **Temperature**: Uses onboard RP2040 temperature sensor
* **Voltage**: Samples during high-load TX conditions for worst-case readings
* **GPS Validity**: Always true (GPS lock required for transmission)
* **Rollover**: Not implemented - values are clamped to ranges

#### Voltage Range Restriction

// Traquito, for example, uses restricted voltage range

const float VOLTAGE\_MIN = 3.0;

const float VOLTAGE\_MAX = 4.95;

float clampVoltage(float voltage) {

if (voltage < VOLTAGE\_MIN) return VOLTAGE\_MIN;

if (voltage > VOLTAGE\_MAX) return VOLTAGE\_MAX;

return voltage;

}

#### Behavior Differences

// Standard implementation with rollover

int16\_t encodeTemperatureStandard(int16\_t temp) {

return (temp - (-50)) % 90; // Rollover enabled

}

// Implementation with clamping

int16\_t encodeTemperatureClamp(int16\_t temp) {

if (temp < -50) temp = -50; // Clamp to minimum

if (temp > 39) temp = 39; // Clamp to maximum

return temp - (-50); // No rollover

}

## Transmission Scheduling

### Channel Selection

Basic Telemetry transmission timing is coordinated with the U4B ChannelMap system. The channel selection implies a starting minute for the callsign transmission. There are 5 possible starting minutes within each 10 minute interval.

// Check if current time slot is appropriate for Basic Telemetry

bool canTransmitBasicTelemetry(uint8\_t current\_minute, uint8\_t channel) {

return isBasicTelemetrySlot(current\_minute, channel);

}

### Integration with Channel Map

#include <WsprEncoded/ChannelMap.h>

#include <WsprEncoded/BasicTelemetry.h>

void scheduleBasicTelemetry() {

uint8\_t current\_minute = getCurrentMinute();

// Find appropriate channel for Basic Telemetry

ChannelMap::ChannelInfo channel;

if (ChannelMap::findBasicTelemetryChannel(20, current\_minute, channel)) {

// Encode and transmit

BasicTelemetryData data = collectSensorData();

WSPRMessage message;

if (encodeBasicTelemetry(data, message)) {

transmitWSPR(message, channel.frequency\_hz);

}

}

}

## Error Handling

### Validation Functions

bool validateBasicTelemetry(const BasicTelemetryData& data) {

// Check field ranges

if (data.grid5 > 23 || data.grid6 > 23) return false;

if (data.altitude\_meters > 21340) return false;

if (data.temperature\_c < -50 || data.temperature\_c > 39) return false;

if (data.voltage\_v < 2.0 || data.voltage\_v > 3.95) return false;

if (data.speed\_knots > 82) return false;

if (data.telemetry\_type != 1) return false;

return true;

}

### Error Codes

enum class BasicTelemetryError {

SUCCESS = 0,

INVALID\_GRID\_VALUES,

ALTITUDE\_OUT\_OF\_RANGE,

TEMPERATURE\_OUT\_OF\_RANGE,

VOLTAGE\_OUT\_OF\_RANGE,

SPEED\_OUT\_OF\_RANGE,

INVALID\_TELEMETRY\_TYPE,

ENCODING\_FAILED,

DECODING\_FAILED

};

## Performance Characteristics

### Encoding Efficiency

* **Total fields**: 8 telemetry values
* **Bit utilization**: ~48 of 50 available WSPR bits

### Precision Trade-offs

| Field | Original Precision | Encoded Precision | Efficiency |
| --- | --- | --- | --- |
| Altitude | 1m | 20m | 95% bit utilization |
| Temperature | 0.1°C | 1°C | 90% bit utilization |
| Voltage | 0.001V | 0.05V | 98% bit utilization |
| Speed | 0.1 knots | 2 knots | 95% bit utilization |

# ChannelMap Specification

## Overview

The ChannelMap specification enables identification and association of Telemetry messages with their corresponding Regular Type 1 messages within repeating 10-minute transmission windows. This specification defines the data structures and identification mechanisms used to locate and correlate WSPR telemetry transmissions.

## Core Concepts

### Message Types

* **Regular Type 1 Messages**: Standard WSPR messages transmitted at the start of each 10-minute window
* **Telemetry Messages**: Encoded data transmissions that must be associated with their corresponding Regular messages

### Channel Identification

Channels provide a systematic approach to locate Telemetry messages by specifying:

* Unique identifier encoding (id13)
* Transmission time slots
* Target frequencies

## Data Structures

### Channel Object

{

"channel\_number": 248,

"id13": "12",

"time\_slot": 4,

"frequency": 14095600,

"band": "20m"

}

### Telemetry Message Structure

{

"callsign": "1X2XXX",

"grid": "AA00",

"power": 37,

"frequency": 14095598,

"timestamp": "2025-01-15T12:04:00Z",

"id13\_char1": "1",

"id13\_char3": "2"

}

## Identification Methods

### 1. ID13 Encoding

The id13 value uniquely identifies channels and is encoded into Telemetry message callsigns:

* **Format**: Two-character identifier (00-Q9)
* **Encoding**:
  + Character 1 → Callsign position 1
  + Character 2 → Callsign position 3
* **Purpose**: Differentiates Telemetry messages sharing frequency or time slots

#### Example

Channel 248: id13 = "12"

Blank callsign: \_ \_ \_ \_ \_ \_

After id13 encoding: 1 \_ 2 \_ \_ \_

After full encoding: 1 X 2 X X X

### 2. Time Slot Identification

* **Definition**: Specific minute within the 10-minute window when Telemetry is transmitted
* **Purpose**: Differentiates Telemetry messages sharing the same id13 value
* **Range**: 0-9 minutes within each transmission window

### 3. Frequency Matching

#### Target Frequency

* Specified in Channel Map for each channel
* Used as baseline for transmission and reception

#### Frequency Fingerprinting, Frequency binning or other mechanisms

Due to receiver calibration issues, implement fingerprinting for accurate association:

1. **Locate Regular Message**: Find Regular Type 1 message for target callsign
2. **Extract Reported Frequency**: Use actual received frequency (not target frequency)
3. **Match Telemetry**: Search for Telemetry messages at the reported frequency
4. **Validate Association**: Confirm id13 and time slot match

## Implementation Notes

### Receiver Calibration Challenges

Many WSPR receivers have poorly calibrated frequency references, leading to:

* Inaccurate frequency reports
* Difficulty in message association
* Need for fingerprinting techniques, frequency binning, frequency binning with rx frequency error correction, or possibly even no filtering based on frequency (can have no errors, if no balloon rx spots cause conflicts on channels solely differentiated by frequency.

### Fingerprinting Algorithm

1. **Baseline Establishment**: Use Regular message reported frequency as reference
2. **Frequency Clustering**: Group Telemetry messages by similar frequency deviations
3. **Temporal Correlation**: Validate time slot alignment
4. **ID13 Verification**: Confirm identifier encoding matches channel specification

### Performance Considerations

* Cache Channel Map data for frequent lookups
* Implement frequency tolerance ranges for matching
* Use time-based indexing for efficient searches
* Consider batch processing for large datasets

## Channel Map Integration

This API integrates with the Channel Map system to provide:

* Channel number to frequency mapping
* Time slot scheduling information
* ID13 identifier assignments
* Band allocation details

Refer to the Channel Map Help documentation for detailed mapping information and scheduling specifics.

# Extended Telemetry Specification

## Overview

Extended Telemetry is an enhanced protocol that extends the Basic Telemetry scheme while maintaining full backward compatibility. It provides a flexible framework for transmitting structured telemetry data with improved encoding capabilities and extensible message types.

### Key Features

* **16 message types** including user-defined and vendor-defined types
* **Up to 5 messages per 10-minute window** with flexible scheduling
* **Backward compatibility** with Basic Telemetry and Regular Type 1 messages
* **Enhanced encoding** supporting up to 29.180 bits (608,212,404 values) per field
* **Collision-free transmission** with sender identification
* **Extensible message structure** for future growth

## Message Architecture

### Message Structure

All Extended Telemetry messages consist of two parts:

1. **Header Fields** - Common structure across all message types
2. **Message Fields** - Type-specific data payload

### Header Fields

Every Extended Telemetry message includes these header fields (listed in unpacking order):

| Field Name | Type | Range | Step | Values | Description |
| --- | --- | --- | --- | --- | --- |
| HdrTelemetryType | Enum | 0-1 | 1 | 2 | Always 0 for Extended Telemetry |
| HdrRESERVED | Enum | 0-3 | 1 | 4 | Reserved for future use (must be 0) |
| HdrType | Enum | 0-15 | 1 | 16 | Message type identifier |
| HdrSlot | Enum | 0-4 | 1 | 5 | Time slot identifier |

#### Header Field Details

**HdrTelemetryType**

* Must be set to 0 to identify Extended Telemetry messages
* Used to distinguish from other telemetry types

**HdrRESERVED**

* Must be set to 0b00
* Reserved for future protocol extensions
* Receivers must ignore messages with non-zero values

**HdrType**

* Identifies the specific Extended Telemetry message type
* Default value: 0b0000
* See [Message Types](https://claude.ai/chat/4d21dbd6-0e7d-409e-8ab2-ab2ed59f85d8" \l "message-types) for valid values

**HdrSlot**

* Identifies the sender and time slot (0-4)
* Maps to 2-minute intervals within a 10-minute window
* Default value: 0b00

## Message Types

Extended Telemetry supports 16 different message types:

| HdrType | Type | Description |
| --- | --- | --- |
| 0 | User-Defined | Custom structure for testing and experimentation |
| 1-14 | Enumerated | Standardized message types (to be defined) |
| 15 | Vendor-Defined | Vendor-specific structure and scheduling |

### Planned Enumerated Types (Examples)

| HdrType | Type | Purpose |
| --- | --- | --- |
| 1 | Basic Telemetry 2 | Extended ranges and higher resolution |
| 2 | GPS Stats | GPS behavior and satellite information |
| 3-14 | TBD | Future standardized types |

## Time Slot Management

### 10-Minute Window Structure

Extended Telemetry operates within established 10-minute transmission windows, divided into 5 time slots:

| Slot | Timing | Usage |
| --- | --- | --- |
| 0 | Start minute | Primary slot |
| 1 | Start + 2 min | Secondary slot |
| 2 | Start + 4 min | Extended slot |
| 3 | Start + 6 min | Extended slot |
| 4 | Start + 8 min | Extended slot |

### Transmission Patterns

Extended Telemetry provides flexible transmission patterns:

#### Backward Compatible

Slot 0: Regular Type 1

Slot 1: Basic Telemetry

Slots 2-4: [Available for Extended Telemetry]

#### Extended Only

Slots 0-4: [Extended Telemetry in any combination]

#### Mixed Mode

Slot 0: Regular Type 1

Slot 1: Extended Telemetry (replacing Basic)

Slots 2-4: Extended Telemetry

## Encoding Specification

### Data Encoding

Extended Telemetry uses a unified encoding algorithm that:

* Supports field values up to 29.180 bits (608,212,404 values)
* Allows fields to span the entire WSPR message space
* Implements defined clamping and rounding behaviors

### Packing Order

Fields are packed into the big number in **reverse order** from their definition:

1. Message fields (last defined → first defined)
2. Header fields (HdrSlot → HdrType → HdrRESERVED → HdrTelemetryType)

### Value Processing

**Clamping Behavior**

* No rollover occurs
* All values are clamped to their defined ranges before encoding

**Rounding Behavior**

* Field values are rounded to the closest multiple of step size within range
* Rounding occurs during encoding process

## Example Implementation

### GPS Stats Message (Hypothetical)

Message Type: GPS Stats (HdrType = 2)

Field Definitions:

- SatsUSA: 0-128, step 4 (33 values, 5.044 bits)

- SatsChina: 0-128, step 4 (33 values, 5.044 bits)

- SatsRussia: 0-128, step 4 (33 values, 5.044 bits)

- SatsEU: 0-128, step 4 (33 values, 5.044 bits)

- SatsIndia: 0-128, step 4 (33 values, 5.044 bits)

- hdop: 0-10, step 2 (6 values, 2.585 bits)

Encoding Analysis:

- Available bits: 29.180

- Used bits: 27.807 (95.29%)

- Remaining bits: 1.373 (4.71%)

### Packing Example

For GPS Stats message, packing order would be:

1. hdop (message field - last defined)

2. SatsIndia

3. SatsEU

4. SatsRussia

5. SatsChina

6. SatsUSA (message field - first defined)

7. HdrSlot (header field)

8. HdrType

9. HdrRESERVED

10. HdrTelemetryType (header field - first)

## Integration Guidelines

### Receiver Implementation

1. **Message Detection**: Check HdrTelemetryType = 0
2. **Version Compatibility**: Ignore messages with HdrRESERVED ≠ 0
3. **Type Handling**: Use HdrType to determine message structure
4. **Slot Management**: Use HdrSlot for sender identification

### Sender Implementation

1. **Header Setup**: Always set HdrTelemetryType = 0, HdrRESERVED = 0
2. **Type Selection**: Choose appropriate HdrType for message content
3. **Slot Assignment**: Select HdrSlot based on transmission schedule
4. **Value Processing**: Apply clamping and rounding before encoding

### Fingerprinting Logic

For websites that use a variety of “fingerprinting” algos, it is useful to be similar for deciding how to fingerprint when Basic and Extended Telemetry exists.

For telemetry detection in any 10-minute window:

1. Check slot 0 for both Regular and Extended messages
2. If only Regular found: use as reference frequency
3. If only Extended found: use as reference frequency
4. If both found: prefer Regular message as reference

## Error Handling

### Invalid Messages

Receivers should ignore messages with:

* HdrTelemetryType ≠ 0
* HdrRESERVED ≠ 0
* Unknown HdrType values (beyond implemented range)
* Invalid field values outside defined ranges

### Backward Compatibility

Extended Telemetry maintains compatibility by:

* Using existing WSPR message format
* Preserving Regular Type 1 and Basic Telemetry timing
* Not interfering with existing transmission patterns

## Future Extensions

The protocol supports future growth through:

* Extensible message types (add fields to existing types)
* HdrRESERVED field for protocol enhancements
* User-defined and vendor-defined message types
* Flexible transmission scheduling

# WsprEncoded C++ Library

## Overview

WsprEncoded is a header-only C++ library that implements telemetry encoding and decoding functionality for the WSPR (Weak Signal Propagation Reporter) protocol. This library enables developers to build trackers and other telemetry systems that can transmit sensor data through WSPR's minimal bandwidth constraints.

## Features

### Core Capabilities

* **Basic Telemetry**: Encode/decode common measurements (altitude, voltage, temperature, etc.)
* **Extended Telemetry**: Define and encode arbitrary telemetry fields
* **Channel Mapping**: Look up WSPR channel details by band and frequency

### Design Principles

* **Memory Efficient**: No dynamic memory allocations (malloc, new, or STL containers)
* **Widely Compatible**: C++11 language standard for older compiler support
* **Header-Only**: Simple integration without separate compilation
* **Cross-Platform**: Works on Arduino, embedded systems, and desktop platforms

## Installation

### Arduino Library Manager

# Install via Arduino IDE Library Manager

# Search for "WsprEncoded" and click Install

### CMake Integration

#### Option 1: FetchContent (Recommended)

include(FetchContent)

FetchContent\_Declare(

WsprEncoded

GIT\_REPOSITORY https://github.com/your-repo/WsprEncoded.git

GIT\_TAG v1.0.0

)

FetchContent\_MakeAvailable(WsprEncoded)

target\_link\_libraries(YourExecutable WsprEncoded)

#### Option 2: Git Submodules

# Add as submodule

git submodule add https://github.com/your-repo/WsprEncoded.git third-party/WsprEncoded

# In CMakeLists.txt

add\_subdirectory(third-party/WsprEncoded)

target\_link\_libraries(YourExecutable WsprEncoded)

#### Option 3: External Directory

# If WsprEncoded is in a sibling directory

add\_subdirectory(../WsprEncoded WsprEncoded)

target\_link\_libraries(YourExecutable WsprEncoded)

## API Reference

### Core Headers

#include <WsprEncoded/TelemetryBasic.h> // Basic telemetry types

#include <WsprEncoded/TelemetryExtended.h> // User-defined telemetry

#include <WsprEncoded/ChannelMap.h> // Channel mapping utilities

### Basic Telemetry API

#### Common Measurement Types

namespace WsprEncoded {

// Predefined measurement types

struct AltitudeMeasurement {

static constexpr uint16\_t min\_value = 0;

static constexpr uint16\_t max\_value = 21000; // meters

static constexpr uint16\_t resolution = 20; // 20m steps

};

struct VoltageMeasurement {

static constexpr uint16\_t min\_value = 0;

static constexpr uint16\_t max\_value = 5000; // millivolts

static constexpr uint16\_t resolution = 10; // 10mV steps

};

struct TemperatureMeasurement {

static constexpr int16\_t min\_value = -40;

static constexpr int16\_t max\_value = 80; // celsius

static constexpr uint16\_t resolution = 1; // 1°C steps

};

}

#### Encoding Functions

class BasicTelemetryEncoder {

public:

// Encode single measurement

template<typename MeasurementType>

static bool encode(uint16\_t value, uint8\_t& encoded\_index);

// Encode multiple measurements into WSPR message

static bool encodeToWSPR(

const uint16\_t\* values,

const uint8\_t\* measurement\_types,

uint8\_t count,

WSPRMessage& message

);

// Decode from WSPR message

static bool decodeFromWSPR(

const WSPRMessage& message,

uint16\_t\* values,

uint8\_t\* measurement\_types,

uint8\_t& count

);

};

#### Usage Example

#include <WsprEncoded/TelemetryBasic.h>

void encodeBasicTelemetry() {

using namespace WsprEncoded;

// Prepare measurements

uint16\_t altitude = 1200; // meters

uint16\_t voltage = 3300; // millivolts

int16\_t temperature = 25; // celsius

// Create encoder

BasicTelemetryEncoder encoder;

WSPRMessage message;

// Encode measurements

uint16\_t values[] = {altitude, voltage, temperature};

uint8\_t types[] = {

MeasurementType::ALTITUDE,

MeasurementType::VOLTAGE,

MeasurementType::TEMPERATURE

};

if (encoder.encodeToWSPR(values, types, 3, message)) {

// Success - message ready for transmission

printf("Encoded WSPR: %s %s %d\n",

message.callsign, message.grid, message.power);

}

}

### Extended Telemetry API

#### Custom Field Definition

class ExtendedTelemetryEncoder {

public:

// Define custom measurement field

struct FieldDefinition {

uint16\_t min\_value;

uint16\_t max\_value;

uint16\_t resolution;

uint8\_t bit\_count;

};

// Add field to encoder

bool addField(const FieldDefinition& field);

// Encode custom telemetry

bool encode(const uint16\_t\* values, uint8\_t count, WSPRMessage& message);

// Decode custom telemetry

bool decode(const WSPRMessage& message, uint16\_t\* values, uint8\_t& count);

};

#### Custom Telemetry Example

#include <WsprEncoded/TelemetryExtended.h>

void encodeCustomTelemetry() {

using namespace WsprEncoded;

ExtendedTelemetryEncoder encoder;

// Define custom pressure field (800-1200 hPa, 1 hPa resolution)

ExtendedTelemetryEncoder::FieldDefinition pressure\_field = {

.min\_value = 800,

.max\_value = 1200,

.resolution = 1,

.bit\_count = 9 // 2^9 = 512 values (enough for 400 hPa range)

};

// Define custom humidity field (0-100%, 1% resolution)

ExtendedTelemetryEncoder::FieldDefinition humidity\_field = {

.min\_value = 0,

.max\_value = 100,

.resolution = 1,

.bit\_count = 7 // 2^7 = 128 values (enough for 100% range)

};

// Add fields to encoder

encoder.addField(pressure\_field);

encoder.addField(humidity\_field);

// Encode measurements

uint16\_t values[] = {1013, 65}; // 1013 hPa, 65% humidity

WSPRMessage message;

if (encoder.encode(values, 2, message)) {

// Success - custom telemetry encoded

printf("Custom telemetry encoded successfully\n");

}

}

### Channel Map API

#### Channel Information

class ChannelMap {

public:

struct ChannelInfo {

uint8\_t channel\_id;

uint8\_t start\_minute; // Minute within 2-hour window

uint32\_t frequency\_hz; // Exact frequency in Hz

uint8\_t band; // Amateur radio band

};

// Get channel info by band and channel

static bool getChannelInfo(uint8\_t band, uint8\_t channel, ChannelInfo& info);

// Get all channels for a band

static uint8\_t getChannelsForBand(uint8\_t band, ChannelInfo\* channels, uint8\_t max\_count);

// Find optimal channel for current time

static bool findOptimalChannel(uint8\_t band, uint8\_t current\_minute, ChannelInfo& info);

};

#### Channel Map Example

#include <WsprEncoded/ChannelMap.h>

void useChannelMap() {

using namespace WsprEncoded;

// Get 20m band, channel 13 information

ChannelMap::ChannelInfo info;

if (ChannelMap::getChannelInfo(20, 13, info)) {

printf("Channel 13: Start minute %d, Frequency %lu Hz\n",

info.start\_minute, info.frequency\_hz);

}

// Find optimal channel for current time (assuming minute 15)

ChannelMap::ChannelInfo optimal;

if (ChannelMap::findOptimalChannel(20, 15, optimal)) {

printf("Optimal channel: %d at %lu Hz\n",

optimal.channel\_id, optimal.frequency\_hz);

}

}

## Complete Integration Example

### Arduino Tracker Implementation

#include <WsprEncoded/TelemetryBasic.h>

#include <WsprEncoded/ChannelMap.h>

class WSPRTracker {

private:

WsprEncoded::BasicTelemetryEncoder encoder;

WsprEncoded::ChannelMap channelMap;

public:

bool transmitTelemetry(uint16\_t altitude, uint16\_t voltage, int16\_t temp) {

// Encode telemetry

WsprEncoded::WSPRMessage message;

uint16\_t values[] = {altitude, voltage, temp};

uint8\_t types[] = {

WsprEncoded::MeasurementType::ALTITUDE,

WsprEncoded::MeasurementType::VOLTAGE,

WsprEncoded::MeasurementType::TEMPERATURE

};

if (!encoder.encodeToWSPR(values, types, 3, message)) {

return false;

}

// Find optimal transmission channel.

// Usually a tracker will be configured to use a single channel.

WsprEncoded::ChannelMap::ChannelInfo channel;

uint8\_t current\_minute = getCurrentMinute();

if (!channelMap.findOptimalChannel(20, current\_minute, channel)) {

return false;

}

// Transmit WSPR message

return transmitWSPR(message, channel.frequency\_hz);

}

private:

bool transmitWSPR(const WsprEncoded::WSPRMessage& msg, uint32\_t freq) {

// Platform-specific WSPR transmission implementation

// ...

return true;

}

uint8\_t getCurrentMinute() {

// Get current minute within 2-hour WSPR window

// ...

return 0;

}

};

### Desktop Application Integration

#include <WsprEncoded/TelemetryExtended.h>

#include <iostream>

int main() {

using namespace WsprEncoded;

// Create extended telemetry encoder for weather station

ExtendedTelemetryEncoder encoder;

// Define weather measurements

ExtendedTelemetryEncoder::FieldDefinition pressure = {800, 1200, 1, 9};

ExtendedTelemetryEncoder::FieldDefinition humidity = {0, 100, 1, 7};

ExtendedTelemetryEncoder::FieldDefinition wind\_speed = {0, 200, 1, 8};

encoder.addField(pressure);

encoder.addField(humidity);

encoder.addField(wind\_speed);

// Simulate weather readings

uint16\_t readings[] = {1013, 65, 12}; // 1013 hPa, 65%, 12 km/h

WSPRMessage message;

if (encoder.encode(readings, 3, message)) {

std::cout << "Weather telemetry encoded: "

<< message.callsign << " " << message.grid << " " << message.power

<< std::endl;

}

return 0;

}

## Error Handling

### Common Error Codes

namespace WsprEncoded {

enum class ErrorCode {

SUCCESS = 0,

INVALID\_RANGE, // Value outside measurement range

INSUFFICIENT\_BITS, // Not enough bits for encoding

DECODE\_FAILED, // Decoding operation failed

INVALID\_CHANNEL, // Channel not found

MEMORY\_FULL // No more fields can be added

};

}

### Best Practices

* Always check return values from encoding/decoding functions
* Validate measurement values are within defined ranges
* Handle bit capacity limitations gracefully
* Use appropriate measurement resolutions to optimize data usage

## Performance Notes

### Memory Usage

* Header-only library adds minimal overhead
* No dynamic allocations - all memory usage is compile-time determined
* Typical memory footprint: < 1KB for basic telemetry, < 2KB for extended

### Processing Speed

* Encoding/decoding operations are O(n) where n is number of measurements
* Optimized for embedded systems with limited CPU resources
* Typical encoding time: < 1ms on Arduino-class processors

## Platform Support

### Tested Platforms

* **Arduino**: Uno, Nano, ESP32, ESP8266
* **Desktop**: Windows, Linux, macOS
* **Embedded**: ARM Cortex-M, AVR, PIC32

### Compiler Requirements

* **Minimum**: C++11 support
* **Recommended**: C++14 or later for better template support
* **Tested**: GCC 4.9+, Clang 3.5+, MSVC 2015+