Low-Cost GNSS Receiver System for Space Weather
Comparison of Results from Low-Cost vs. High-End Receivers

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Recommendation of the ICG, Working Group C on Information Dissemination and Capacity Building:
➢ Establish a project team within the WG-C to explore the possibilities of using low-cost GNSS receivers for space weather monitoring.

● Objectives
  ● Explore Low-Cost GNSS Receivers that can be used to compute ionosphere-related parameters TEC, S4 and other parameters.
  ● Explore software that can be used for processing data from low-cost GNSS receivers to compute TEC, S4 and other parameters.
  ● Develop a prototype low-cost GNSS receiver system for space weather applications.

● Project Team Members
  ● Sharafat Gadimova, United Nations Office for Outer Space Affairs, ICG Executive Secretariat, Austria
  ● Dinesh Manandhar, Center for Spatial Information Science (CSIS), The University of Tokyo, Japan
  ● Christine Amory-Mazaudier, Laboratory of Plasma Physics (LPP), France
  ● Bruno Nava, International Centre for Theoretical Physics (ICTP), Italy
  ● Gabriella Povero, Centre for Earth Observation, Italy
  ● Keith Groves, Boston College, United States of America
How to Make a Low-Cost GNSS Receiver System?

- **GNSS Module or Receiver**
- **Micro-Controller or Micro-Processor**
- **Memory**
- **External Memory Device**
- **External Interface**
- **WiFi, BT, Ethernet, MQTT, IoT links**
- **Single Board Computer**
- **Raspberry Pi**, **Arduino**
- **Hard Disk**
- **WiFi**, **BT**, **Ethernet**, **MQTT**, **IoT** links

- **Note**: We use these modules for high accuracy positioning systems based on RTK and MADOCA PPP or other GNSS/QZSS special applications.

- **There are many other GNSS modules as well. We have no intention of any purpose to name some of the makers here.**

A smart-phone has everything that we need
- **CPU**
- **Memory**
- **External Interface**
- **GNSS Receiver**
- **Sensors**

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Low-Cost High-Accuracy Receiver system Development Cycle

DEC, 2016
Raspberry Pi B
Demo during UN/Nepal GNSS workshop

MAY, 2017
Low-Cost RTK

MAR, 2018
Low-Cost MADOCA

What Application or System Do you want?

- Enhancement of MADOCA System 2022 / 2023
- Android Device based Applications RTK / MADOCA / EWS / SAR
- Space Weather Applications
- Dynamic Air Quality Monitoring System

2022 - 2023
Low-Cost High-Accuracy GNSS Receiver System: Space Weather Applications

We will explore at least two types of receivers
- u-blox F9P (L1/L2 or L1/L5)
- Septentrio (MOSAIC) (L1/L2/L5)

Criteria for Receiver Selection
- Any receiver that is capable to output raw data
- Dual frequency receiver
- Price less than $1,000

<table>
<thead>
<tr>
<th>Feature</th>
<th>U-Blox F9P</th>
<th>Septentrio MOSAIC</th>
<th>Other Brand</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS</td>
<td>GPS, GLONASS, Galileo, BeiDou, QZSS, SBAS</td>
<td>GPS, GLONASS, Galileo, BeiDou, QZSS, SBAS</td>
<td></td>
</tr>
<tr>
<td>Frequency Bands</td>
<td>L1, L2, E5b or L1, L5, E5a</td>
<td>L1, L2, L5 or L1, L2, L6*</td>
<td></td>
</tr>
<tr>
<td>Raw Data</td>
<td>Code Phase, Carrier Phase, Doppler, Signal quality related data</td>
<td>Code Phase, Carrier Phase, Doppler, Signal quality related data</td>
<td></td>
</tr>
<tr>
<td>Navigation Frame Data</td>
<td>Yes including data bits</td>
<td>Yes including data bits</td>
<td></td>
</tr>
<tr>
<td>Output Rate</td>
<td>Max 20Hz</td>
<td>Upto 100 Hz for Measurement 50Hz for RTK</td>
<td></td>
</tr>
<tr>
<td>RTK / PPP Capable</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>TEC Computation</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>S4 / φ4 Computation</td>
<td>May be (To be explored)/ No</td>
<td>May be (To be explored) / No</td>
<td></td>
</tr>
<tr>
<td>Price (USD)</td>
<td>300</td>
<td>700</td>
<td></td>
</tr>
</tbody>
</table>


Note: We have no preferences of whatsoever on any brand or name. The receivers are selected based on our selection criteria. Any suggestions on receiver types are highly appreciated.

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Low-Cost GNSS Receiver System for Space Weather Applications
Remote and Unattended Continuous Data Logging

- Design a low-cost GNSS receiver system for unattended data logging
  - Integrate receiver with micro-computer
    - RaspberryPi / ESP32 / Android Device
- Explore different types of configurations
  - Type – A : based on RaspberryPi device
  - Type – B : based on ESP32 device
  - Type – C : based on MOSAIC (Septentrio)
- Requirements
  - Automatically log raw data when power is connected.
  - Automatically connect remote server
  - Recover all setups when the receiver is reset
  - Log raw data locally in a SD Card.
Low-Cost GNSS Receiver System for Space Weather Applications

Software for Data Processing: TEC and S4 Parameters

Output of TEC computation from Matlab based software: FLEURY

Explore software that can be used for processing data from low-cost GNSS receivers to compute TEC, S4 and other space weather-related parameters.

- **FLEURY**
  - Matlab source code available

- **K-TEC**
  - Matlab Source code available

- **NeQuick**
  - Software is available at:
    - [https://www.itu.int/rec/R-REC-P.531-14-201908-I/en](https://www.itu.int/rec/R-REC-P.531-14-201908-I/en)

Matlab source files to compute TEC parameters are provided by Rolland Fleury

These outputs are from sample data provided by Fleury

We will modify the software to process data from low-cost GNSS receivers

**K-TEC: From KMITL, Thailand**
Comparison of High-End vs. Low-Cost GNSS Receiver for TEC/ROTI
Data Observation Method

Items | Values
--- | ---
Approximate position: PolarRx5 | [Lat (°), Lon (°), Height (m)]
 | [35.903, 139.939, 89.159]

Fleury: Software by Robert Fleury
K-TEC: Software by KMITL, Thailand
ICTP-B: Software by B. Nava, ICTP

KMITL: King Mongkut Institute of Technology, Ladkrabang, Thailand
ICTP: International Center for Theoretical Physics, Italy
GNSS Observation Data (K-TEC)

- RTKCONV (demo5, b34g) is used to convert proprietary data into RINEX 3.04 format
- The OBS data files are read by readrinex304 (mexw64 file)

Convert proprietary data into RINEX 3.04 data format

<table>
<thead>
<tr>
<th>GNSS Receivers</th>
<th>Observation Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS (G)</td>
<td>C1C L1C S1C C2X L2X S2X C5X L5X S5X</td>
</tr>
<tr>
<td>GLONAS (R)</td>
<td>C1C L1C S1C C2C L2C S2C</td>
</tr>
<tr>
<td>Galileo (E)</td>
<td>C1X L1X S1X C5X L5X S5X</td>
</tr>
<tr>
<td>QZSS (J)</td>
<td>C1Z L1Z S1Z C2X L2X S2X C5X L5X S5X</td>
</tr>
<tr>
<td>SBAS (S)</td>
<td>C1C L1C S1C</td>
</tr>
<tr>
<td>BeiDou (C)</td>
<td>No SW License to log data</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed date</td>
<td>June 18, 2023</td>
</tr>
<tr>
<td>Height (Iono-pierce point)</td>
<td>350 km</td>
</tr>
<tr>
<td>Elevation mask</td>
<td>30°</td>
</tr>
<tr>
<td>ROTI window size</td>
<td>5 min</td>
</tr>
</tbody>
</table>
Since the same antenna is used, the VTEC from all receivers has similar trends and levels.
ROTIT Results (K-TEC)

Net-R9 (C1C-C2X)

PolarRx5 (C1C-C2W)

MOSAIC (C1C-C2W)

U-box F9P (C1C-C2X)
The low-cost receiver VTEC values have similar results to the high-end receiver VTEC values.

MOSAIC receiver VTEC values are equivalent to PolaRx5 receiver VTEC values.
Comparison of VTEC Results: Computed by ICTP-B (Bruno Nava)

vTEC  168–169–170  23  KSF9  KSMS  KSR9  KSX5

KSR9  ->  Trimble NetR9
KSX5  ->  Polaris X5
KSMS  ->  mosaic
KSF9  ->  ublox
Future Works:
(a) Test more receiver types
(b) Test more antenna types
(c) Compute using different software
Summary

- Low-Cost GNSS Receivers are getting powerful for Space Weather applications
  - TEC and ROTI Parameters can be computed
- Need to develop software so that low-cost receiver systems can be used
  - Easy integration with other systems
  - Signal analysis for various applications such as TEC, ROTI, Scintillation computation
- Current results show that TEC/ROTI can be computed using low-cost receivers
  - TEC preliminary results are satisfactory. Requires further studies on computation
- Data formats and processing algorithms shall be standardized for uniform results
- Need to inform and request receiver manufacturers to provide necessary outputs
  - It helps to reduce the cost
  - Output required for space weather is too heavy in terms of memory and CPU that consumes power, so manufacturers are not happy to output raw data
  - But, it might be possible to output by using a special firmware for scientific applications
- Necessary to have close collaboration between the GNSS community and the Space Weather Community
  - We are planning to install multiple low-cost GNSS receivers in Asian countries to explore the possibilities of space weather applications
  - We need your help!