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Discussions

A new permanent multi-parameter monitoring network in Central Asian high mountains – from measurements to data bases

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Abstract

Long-term monitoring of water resources and climate parameters at the scale of river basins requires networks of continuously operated in-situ stations. Since 2009, GFZ and CAIAG, in cooperation with the National Hydrometeorological Services (NHMS), are establishing such a regional monitoring network in Central Asia (Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, and Afghanistan) which is collecting observations of meteorological and hydrological parameters and delivering them to the end-users. The network design focuses mainly on the higher elevations where the recent decline of monitoring stations and networks established in Soviet times was strongest, and the resulting observational gap hinders research on climate and hydrological change as well as operational tasks in water management such as the seasonal runoff forecast.

The newly developed and installed Remotely Operated Multi-Parameter Stations (ROMPS) do not only monitor standard meteorological and hydrological parameters, but also deliver GPS data for atmospheric sounding as well as tectonic studies. The observational data from the ROMPS is transmitted at least once a day to a centralized geo-database infrastructure for long-term storage and data redistribution. Users can access the data manually using a web-interface or automatically using SOS requests; in addition, data is distributed to the NHMS through standard communication and data exchange channels.

1 Hydrometeorological monitoring in Central Asian headwaters – a technical challenge

In the arid to semi-arid region of Central Asia (Fig. 1), water is a crucial resource both for the fresh water supply to the growing population as well as a necessary prerequisite for the economic development of the five former Soviet Republics in Central Asia – Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Both of the two main rivers in Central Asia – the Amudarya and Syrdarya – originate in the Central

Asian high mountains and their flow is formed from the melt of seasonal snow pack, glacier ice and warm season rain. This important role of the flow formation zone for water management in Central Asia calls for a continuous monitoring which provides data needed for operational seasonal runoff forecast as well as the assessment of changes in the headwater catchments and their water resources.

In the past decades, hydrometeorological monitoring in Central Asia was largely based on manned outposts. Data was collected manually and sent by telephone or radio to centralized data management centers. After the collapse of the Soviet Union, it became increasingly difficult for the new independent Republics to maintain the existing monitoring network in Central Asia due to funding limitations. The resulting network decline primarily affected stations in the flow formation zone in altitudes above 2000 m a.s.l. (e.g. World Bank, 2009; Finaev, 2009). In Kyrgyzstan alone, the number of meteorological stations decreased from 83 stations in 1985 to 30 stations in 2000, the number of hydrological stations from 147 to 75 stations in the same period (Itibayev, 2009).

Hence, there is a great need for improvement of hydrometeorological monitoring in Central Asian headwater catchments. In the 1990s and 2000s, several internationally funded projects already addressed this issue and have succeeded to install a number of automatic monitoring stations; most prominent among them is the rehabilitated station at the Fedchenko glacier in the Pamir Mountains (Kayumov et al., 2002). Yet, there remain a number of challenges:

1. more stations are needed to consolidate the monitoring network especially at higher altitudes,

2. the additional stations need to be capable of reliable un-manned operation under the prevailing extreme environmental conditions in remote areas, have low maintenance requirements and, additionally, incur low operational costs at the same time,

3. near-real time data transmission to data users is needed,

4. a data management infrastructure capable of facilitating data sharing among all countries of the region has to be implemented.

Those challenges are addressed in the frame of the CAWa project (www.cawa-project.net) and the "Global Change Observatory Central Asia (GCO-CA)" of the German Research Centre for Geosciences (GFZ) where German and Central-Asian scientists and specialists are establishing a regional hydrometeorological monitoring network of ROMPS with a special focus on the flow formation zone.

This paper is organized as follows: in Sect. 2 we present the ROMPS design and individual components including sensors, operation control facilities and communication lines. In Sect. 3, the data management unit (System Operation, Processing and Archiving Facility) is described. Section 4 demonstrates some examples of station implementations. We finalize the paper with a short discussion of the capabilities and limitations of the developed monitoring network approach and give conclusions for future activities.

2 The ROMPS concept of the CAWa/GCO-CA network

Against the background of degrading monitoring networks in Central Asian headwater catchments, remotely operated multi-parameter stations (ROMPS) offer great opportunities to support a wide range of societal and scientific tasks, among them weather observations and forecasts, long-term climate monitoring, river discharge monitoring and forecasts, crustal deformation and earthquake monitoring as well as the establishment of water-related early-warning systems. To serve those purposes, such stations have to combine different sensor types at one station and share power supply and communication devices while minimizing operational costs. The ROMPS station concept (Fig. 2) presented in this section is based on the concept of GPS-controlled tide gauges which were developed as a component of the German-Indonesian Tsunami Early Warning System (Schöne et al., 2011).

2.1 ROMPS concept and hardware

The ROMPS integrate various sensors used in different geo-scientific disciplines (Fig. 3). The general and open concept provides a ready platform to add more sensors, either by attaching the new hardware or by connecting external independent sensors through dedicated software components (e.g. seismometers using the SeisComP software, see Hanka et al., 2000).

Common to all ROMPS is a computer module (PC) and a power module. The PC module consists of a low-voltage embedded computer based on the PC/104 standard with extension cards and an 8 GB flash drive. The PC has a small Linux distribution installed to perform all station relevant tasks such as basic system operation, logging and storage of sensor data, data transfer via the satellite communication and system management and control (in particular, control of flash disk and power status). With a power consumption of 3 Watt and an operating temperature ranging between −60 °C and +50 °C, the PC module is suited for remote sites and extreme environmental conditions. The module also integrates a battery manager for managing several power lines that independently provide power to the sensors, data loggers and communication components. A keep-alive function to the PC module controlled by the battery manager monitors the response time of the PC and, in case of failure, re-powers it.

The power module operates as a load balancer between up to three different external power sources, such as the solar arrays and a generator (if a local power line is available) and two independent battery circuits. The power module provides load and charge values accessible at a serial port interface to the PC and allows a dedicated power management. Depending on the current power level, hardware can be temporarily disconnected from the main system through the battery manager to preserve the base functionality of the ROMPS (see e.g. Fig. 9b).

To provide sufficient power even during winter and bad-weather conditions, up to six solar panels with 520 Wp peak power and six batteries with 250 Ah capacity each are installed. Permanent operation of the batteries is secured in a temperature range

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down to −40 °C, while in extreme conditions they survive also a minimum temperature of −60 °C.

2.2 Sensors

The ROMPS are equipped with standard components meeting the official WMO requirements (WMO, 2008). The connected hydrometeorological sensors (for details see Table 1) are operated by and their data is stored at a Campbell® Scientific Instruments CR1000 data recorder. As a standard common to all stations, the following sensors are integrated: wind sensor, combined air temperature and relative humidity probe, air pressure sensor, a tipping bucket for rain monitoring and a 4-component net radiation sensor to measure the ratio between the incoming short-wave and long-wave infrared radiation versus surface-reflected short-wave and outgoing long-wave radiation. Optionally, up to six soil moisture and soil temperature sensors complement the station setup. All sensors are sampled every five minutes. The data is downloaded from the data recorder to the PC and transferred preferably on an hourly basis by the satellite communication system to the System Operation, Processing and Archiving Facility (SOPAF) system (see Sect. 3) for further processing and distribution.

For head water monitoring, information about snow height and snow properties as well as river discharge are crucial. Snow parameters are measured using a snow pack analyzing (SPA) system (Sommer, 2009) together with a temperature-compensated ultrasonic snow depth sensor. The SPA consists of four flat-ribbon sensors (SPA-sensor) along which the complex impedance is measured at different frequencies. Based on the dielectric constants of the three components ice, water and air in the snow, the SPA-sensor derives information about the snow density and the liquid water and ice content of the snow pack. In combination with the snow depth sensor, the snow water equivalent is calculated. The SPA is sampled at 15 minute intervals.

River discharge monitoring is continuously performed using a RQ-24 Doppler-based radar sensor (Sommer, 2008) measuring the surface velocity of the river water. In

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combination with a time-delay measurement (pulse radar), the water level height can be determined. The discharge can be calculated by the sensor if the system has been calibrated by integrating values for the river cross section area and the mean flow velocity. In the field, the sensor is installed under bridges and provides water level and flow velocity data in a non-contact and failsafe way even under high discharge, flooding and turbulent flow regimes.

Additionally, all ROMPS integrate a continuously operated geodetic Global Navigation Satellite System receiver (GNSS) providing 1 Hz sampling. The dense sampling is suitable for high-rate applications in dynamical deformation monitoring such as earthquake events. In most applications, however, only sub-sampled data is used, primarily to monitor tectonic plate movement and to derive precipitable water vapor (PWV) in the atmosphere. Here, SOPAF provides the GNSS processing functionality. GNSS phase observations are first converted to RINEX format (Gurtner and Estey, 2007) and then processed together with global GNSS station data from the International GNSS Service (IGS) (Dow et al., 2009) using GAMIT software (Herring et al., 2009). From the processing results the time-varying zenith wet delay is combined with information from meteorological sensors for estimating the PWV distribution in the atmosphere (e.g. Bender et al., 2008). The derived PWV values are stored in and made accessible through SOPAF (Sect. 3).

Optionally, seismological sensors (either broadband or strong motion sensors) can be connected to and completely handled by the station. The seismic data is delivered to the international GEOFON network using the SeisComP software (Hanka et al., 2000) through the stations VSAT communication system.

At some ROMPS also automated high-rate digital optical cameras are integrated. They are used for continuous monitoring of glacier mass balances by observing the snow line and the percentage of snow coverage on the glacier (Huss et al., 2011). In addition, the pictures allow the validation of selected hydrometeorological measurements, such as snow height. The pictures taken by the cameras are stored on the station's PC and transmitted to SOPAF for further distribution.

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2.3 Station operation and software

All ROMPS are operated and managed by several software components and scripts (Fig. 4) running on the PC module (see Sect. 2.1). Based on the Linux operating system, several sh/csh and perl scripts have been developed to provide the basic functionality, e.g. for the watchdog function, data communication, backups, malfunction recovery and the disk management. Additionally, each attached hardware device (e.g. GPS or Campbell® data recorder) is operated by using dedicated C-based software applications. The software modules manage the hardware by collecting and storing data at predefined intervals and provide house-keeping data and self-test capabilities. The power management is provided by the battery manager as part of the PC module. The power lines can only be switched on by software applications if sufficient power is available. If the power drops below the individually defined thresholds, the hardware is switched off automatically until power recovery. With the managing software taking care for those limits, the station's hardware can be operated with minimal interruptions. Due to the effective power management design the only hardware device occasionally affected by power limitations is the VSAT communication system with its 4 A power consumption. Thus, especially in winter time, the VSAT communication may be terminated temporarily by the control of the battery manager.

2.4 Data communication

Permanent monitoring sites require independent, stable and cost-effective communication lines. For urban areas a multitude of communication techniques exist, including local area networks (LAN) or the general packet radio service (GPRS). In remote areas, satellite-based communication provides the only reliable site access. Some remote installations use one-way communication only, e.g. through the GTS system (EUMETSAT, 2009) or meteor burst communication technology (Schilling, 1993), as a reliable and cost-effective but low-bandwidth system. On the other hand, multi-sensor stations like ROMPS with their different types of data streams require higher bandwidth, real-time access and a two-way communication line. Only few systems are meeting those requirements, among them very-small-aperture terminals (VSAT) (e.g. Angermann et al., 2010), Inmarsat's Broad Band Global Area Network (BGAN) system (Inmarsat, 2009) and low-bandwidth satellite-based communication systems like IRIDIUM (Iridium, 2010).

For the long-term operation of permanent monitoring systems, communication costs are essentially contributing to the total operational costs. Hence, for the selection of the main communication system, total costs (i.e. the combination of the initial investment, depreciation and effective annual costs for bandwidth) have to be considered. Table 2 gives an overview on the characteristics of three satellite-based two-way communication systems.

For the CAWa/GCO-CA network in Central Asia, VSAT was chosen as the primary communication tool. Especially the scalable bandwidth and high bandwidth/cost ratio make long-term operation sustainable. Since all stations use a bundled bandwidth, partner organizations in the different Central Asian countries do not need individual service provider contracts. All installations use the iDirect 3000 Series Satellite Router with a Ø 1.8 m Prodelin Ku-band antenna. Data access is established via the EXPRESS AM22 satellite to a central hub in Vienna (Austria).

As shown before, VSAT installations are demanding in terms of power consumption. Nonetheless, the experience with the now installed five ROMPS in Central Asia showed that even for high-mountain installations with sometimes limited sun exposure, the stations can be operated 24 h a day with a minimum of two hours of daily communication access. In summer periods, up to 24 h of data access is usually possible.

As a redundant communication line an IRIDIUM SCV-X modem is integrated into the stations. Due to the low bandwidth and high per-minute charge, this modem is only used for backup and as a backdoor for basic system operation while VSAT is used to continuously transmit the data to SOPAF.

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3 System Operation, Processing and Archiving Facility (SOPAF)

As outlined in the previous sections, the System Operation, Processing and Archiving Facility (SOPAF) is the central IT-platform of the CAWa monitoring network and serves to collect and integrate information obtained from heterogeneous information resources as well as to support the integration of various data types such as meteorological, hydrological, GNSS or seismic data. It also provides dissemination functions for the observations and processing results to different user groups via web-based services. Therefore, SOPAF must meet the following requirements:

- The ability to interact and communicate with different types of resources (sensor stations, virtual sensor networks, processed data).
- The ability to add new stations, new types of sensors as well as copies of existing sensor types or processing results.
- Allow access to the data (display and download functions) for external users using standard Internet browsers, HTTP-requests or applications running in Java Web Start.
- The ability to communicate with existing monitoring networks (e.g. those operated by the national Hydrometeorological Services) using standard exchange protocols. This requirement enables users to easily integrate requests to SOPAF into their operational standard procedures. For data exchange common formats are used, e.g. CREX (ECMWF, 2006) and KN1 (a format widely used in the former Soviet Union, and today, in many Central Asian countries).
- The portability to different operating systems. To achieve a maximum independence from operating systems, JAVA was selected as the programming language. In addition, Java Enterprise Edition platform provides already tools to access the system via the Internet protocols (e.g. http).

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– Support the re-use of software components in client applications. An Open Standard Interface including software for developers of special applications should be provided.

Observational networks are tending to be or to become inhomogeneous over time in their used data formats, the data transfer protocols and / or the used communication lines. In order to be able to adapt to these changes in the long-term, SOPAF's implementation is based on the standards of the Sensor Web Enablement (SWE) initiative (Chu et al., 2006) of the Open GIS Consortium (OGC, 2010) that defines standardized service interfaces for the access of sensor data and networks. SWE completely hides the heterogeneity of the sensor network to the user and simplifies the access to the data. SOPAF is built on the basis of the Tsunami Service Bus (TSB) (Fleischer et al., 2010). As the TSB, SOPAF is acting as an integration platform providing interfaces and services for the access to sensor data following the SWE standards like the Sensor Observation Service (SOS) (SOS, 2007).

3.1 Information model for measurements

The SOPAF internal data model is based on the SWE Observation and Measurement specification (O & M, 2010) in combination with the SOS standard data model (SOS, 2007) consisting of the following objects: *FeatureOfInterest*, *Observation*, *Phenomenon*, *CompositePhenomenon*, *Procedure*, and *Offering*. To integrate the observations from the "physical world" into the "abstract world" of the SWE standard, a mapping is necessary (Table 3). To ensure an easy access to the data for end users from different disciplines the overall information is organized by certain *Offerings*. For example, current *Offerings* are "meteorology", "hydrology", "seismology", or "GPS measurements". Based on WMO standards (WMO, 2008), meteorological and hydrological parameters being physically related to each other are grouped as *CompositePhenomenon*, e.g. "Temperature, Pressure, Humidity", "Surface wind", "Precipitation", "Radiation", or "Soil Moisture".

3.2 Interfaces to SOPAF

As outlined in Sect. 2.2, the installed ROMPS measure a wide range of currently about 100 meteorological, hydrological and geophysical parameters, a number which might easily be expanded in the future.

In order to provide convenient access to the measured parameter sets, SOPAF offers two levels of interfaces, (1) a web service and (2) a Graphical User Interface (GUI). For the public web interface service SOPAF implements three core operations which correspond to the "core profile" set of operations as defined by the SOS: *GetCapabilities*, *GetObservation* and *DescribeSensor*. The function *GetCapabilities* is used to acquire meta-information about the content of the data base system or of an individual sensor. Based on this information, *GetObservation* queries specific information on the measured physical values. The request *DescribeSensor* is used to provide all meta-information about a particular sensor. To assist user specific developments a web-based "SOS Test client" has been implemented (http://cawa.gfz-potsdam.de:8080/SOS/, see Fig. 5) providing examples of all three functions in XML format.

For those users who do not wish to directly integrate SOS requests to SOPAF into their Information Systems, a Graphical User Interfaces (GUI) can be used to extract information from SOPAF and to export data into e.g. comma-separated value (CSV), Microsoft Excel (xls), CREX (ECMWF, 2006) or KN1 formatted files (http://cawa.gfz-potsdam.de:8080/Availability/, see Fig. 6).

3.3 IT infrastructure and implementation

SOPAF collects all observations from the CAWa and GCO-CA hydrometeorological network and serves as the main point for data access. It is also able to integrate data provided by other data services, e.g. from the National Hydrometeorological Services). A generalized diagram of the interaction between individual SOPAF components is outlined in Fig. 7.

Through the satellite communication, formatted or binary data is uploaded by FTP from the ROMPS to two centralized servers at CAIAG in Bishkek, Kyrgyzstan, and to GFZ in Potsdam, Germany. Several parallel-operating retrievers are configured for the different sensor types and for dedicated file types. After file arrivals the retriever sends the station data to the dispatcher which translates and writes the proprietary formatted information into the SOPAF data model.

As hardware infrastructure, SOPAF uses two independent but identical Sun Fire X4600 servers to increase the access availability and to allow a faster data access in both from Central Asia and the world. The base operating system of the computers is NOVELL SUSE Linux Enterprise 11, which controls Ubuntu 10.04 in virtual machines. For the realization of the SOPAF system, the JAVA EE technology[1], Enterprise JavaBeans[2], JavaServer Faces Technology (JSF)[3], Java Message Service (JMS)[4] and the Extensible Markup Language (XML) were chosen as developing tools. The data model is implemented in the object-relational database management system PostgreSQL (www.postgresql.org) Version 8.4. The application server JBoss Version 4.2.3 (www.jboss.org) manages all software components of SOPAF.

4 CAWa and GCO-CA monitoring network

This section describes the current status of ROMPS installations in Central Asia. A map of the current and planned station locations is shown in Fig. 8. In addition, two exemplary stations are described in more detail.

All stations have an identical set of meteorological sensors and only a few different types of geodetic GPS receiver (Table 5). Additionally, some stations have site specific

[1]http://www.oracle.com/technetwork/java/javaee/tech/index.html
[2]http://www.oracle.com/technetwork/java/javase/tech/index-jsp-138795.html
[3]http://www.oracle.com/technetwork/java/javaee/javaserverfaces-139869.html
[4]http://www.oracle.com/technetwork/java/jms/index.html

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installations of snow measuring systems or river discharge sensors. This set of sensors from a limited number of manufacturers simplifies the station management and requires only minimal resources for maintenance. Table 6 gives the names and locations of stations planed for installations in 2012 and 2013.

4.1 Station Taragay

Since 2010, Taragay station is monitoring hydrometeorological parameters in the Naryn catchment area. There has been a predecessor station operated by CAIAG equipped with continuous GPS, a broadband seismometer and a compact meteorological sensor. While the GPS and seismometer are continuously used in the new station, the compact meteorological sensor was replaced by the standard hydrometeorological equipment. The data is transmitted by a VSAT connection to SOPAF. The seismometer which is contributing to the GEOFON network (Hanka et al., 2000) shares the bandwidth of the VSAT link.

This station perfectly demonstrates the availability and limitations of the data connection in terms of seasonal variations in sunshine duration. Due to the high power consumption of the VSAT, data communication is continuously operated during summer time when the solar input is available for 8 to 14 h. Between late autumn and early spring the on-time is reduced to a few hours daily, depending on the solar input. Figure 9a shows the power balance (charge versus load, VSAT on-times, time of positive power balance) and Fig. 9b compares the power supply for the summer and winter solstice.

4.2 Station Abramov glacier

The Abramov glacier is located in the Alai range in Southern Kyrgyzstan draining towards the Vaksh river. Between 1967 and 1999 a permanent glacier observatory adjacent to the glacier had been operated by the Central Asian Research Institute for Hydrometeorology (SANIGMI) in Tashkent. The data of this period is published in

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Pertziger (1996). In 1999 the station was vandalized and destroyed but rehabilitated in August 2012 with a ROMPS. The main research of the former station was focused on continuous glaciological, hydrological and meteorological measurements. Logistical constraints and site security issues had required a slight re-location of the new automated station to a higher position. The suite of sensors comprises standard meteorological equipment (see Tables 2 and 5). In addition, two surveillance cameras, installed by the World Glacier Monitoring Service (WGMS, www.wgms.ch) and connected to the base station by a LAN cable (camera #1) and a radio modem (camera #2), are monitoring most of the snow accumulation and ablation area and the glacier tongue twice a day (Fig. 10). Based on the analysis of these frequent camera pictures in combination with ablation stake readings, glacier mass balance studies can be carried out (e.g. Kaser et al., 2003). The installed SPA (Sommer, 2009) delivers information about the accumulated snow and its properties. This combination will allow the prediction of the onset time of melting as well as the estimation of water availability during the melting period.

This station also demonstrates the simple integration of additional non-traditional sensor types or systems to the ROMPS, like camera systems. The station completely handles all connected systems and automatically transfers the data to the SOPAF system for long-term storage and distribution to the users.

5 Discussion and conclusions

Hydrometeorological monitoring in Central Asia requires an upgrade and extension of the existing ground monitoring network and the establishment of a widely accepted information infrastructure to ensure the long-term storage of data and data products and an open and unrestricted data access. In the past years, the CAWa/GCO-CA projects contributed to those challenges by establishing five permanent ROMPS in Central Asian headwater catchments, and SOPAF as a data management infrastructure.

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The ROMPS of the CAWa/GCO-CA network are designed for long-term monitoring under harsh and varying climate conditions. Even under un-attended operation, they show excellent performance. With the capability for easy upgrades and the possibility of extensions with third-party equipment there is a wide range of applications. Another advantage is the selectable communication infrastructure. The drawback of the ROMPS concept is the high initial investment. Thus, the main application field remains in high-altitude areas and un-attended installations. For the future perspective, such a monitoring network has a high potential for the development of Early Warning/Multi-Hazard monitoring applications in a region like Central Asia which is heavily affected by water-related geo-risks, such as land slides, flash floods and glacier lake outburst floods (UNISDR et al., 2009).

The System Operation, Processing and Archiving Facility (SOPAF) as the network's central IT-platform serves to collect and integrate information gathered from the network. All data is freely available trough two mechanisms. The first is SOS requests (GetCapabilities, GetObservation, DescribeSensor) suitable for integration of SOPAF features into user-specific Information Systems. The second is a web-based GUI, which allows individual researchers to access information on a predefined way using several output formats. In the future, SOPAF is planned to integrate and re-distribute also information and measurements from external networks. The selected SWE standard and the SOS support the implementation of new phenomena (*Phenomenon*) or new stations (*Procedure*).

In addition to the before mentioned applications, the observational data from the monitoring stations is used as "ground truthing" data for new space-borne monitoring techniques, e.g. in the frame of the CryoSat, EnMap, and GRACE missions (Helmholtz Association, 2012).

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Table 1. Primary hydrometeorological sensors used in the CAWa/GCO-CA network.

Sensor	Manufacturer	Observed parameters	Sampling interval
Wind Monitor 05103	RM Young, USA	Wind direction, wind speed	5 min
Tipping Bucket Rain Gauge 52203	RM Young, USA	Precipitation	5 min
Temperature & Relative Humidity Probe HMP45	Vaisala, Finland	Air temperature, relative humidity	5 min
Net Radiometer NR01	Hukseflux, The Netherlands	Solar short wave and far infrared long wave radiation (incoming and out-going)	5 min
Barometric Pressure Transducer 278	Setra, USA	Barometric air pressure	5 min
Soil Water Content Reflectometer CS616	Campbell Scientific, UK	Volumetric water content	5 min
Soil Temperature Sensor 107	Campbell Scientific, UK	Soil temperature	5 min
Discharge System RQ-24	Sommer, Austria	Water level, river surface flow velocity, river discharge	15 min
Snow Pack Analyzing System (SPA)	Sommer, Austria	Snow depth, snow density, snow water equivalent, contents of liquid water and ice	15 min

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Table 2. Operational characteristics of satellite-based two-way communication systems (for power consumption, bandwidth and cost ratio).

	Power Consumption @ 12 V transmit/receive/stand-by (A)	Bandwidth (Kbps)	Bandwidth/Cost ratio
VSAT	4/4/4	>30 (scalable)	High
BGAN	1/1/0.5	>150	Low
Iridium	0.45/0.24/0.12	0.3	very low

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Table 3. Relationship between SWE definitions and their mapping to SOPAF components.

SOS object name	Description and corresponding names in SOPAF
FeatureOfInterest	Geo-referencing of the sensor, assignment to the location of the *Observation* (e.g. sensor station names: Abramov_Station, Baitik_Station, etc.).
Procedure	Creates the type of observation (*Phenomenon*) by a sensor, simulation product or processing results (in SOPAF *FeatureOfInterest* is identically used to *Procedure*).
Observation	Measured value created by a sensor related to a distinct time or period
Phenomenon	Type of an *Observation* (e.g. air temperature, wind speed, rain), related to the *FeatureOfInterest* (Table 4).
CompositePhenomenon	Grouping of several physically related phenomena (*Phenomenon*) (e.g. *CompositePhenomenon* "Surface wind" is composed of phenomena (*Phenomenon*) wind speed, gust and wind direction).
Offering	Group of *Observation*(s) offered by a service (e.g. web site) to the user (e.g. meteorology, hydrology, seismology, GPS measurements).

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Table 4. "*CompositePhenomenon*" defined by combining SOPAF-"*Phenomenon*". The SOS construct of "*CompositePhenomenon*" (SOS, 2007) gives users a more convenient access to observed quantities, which are physically closely related. The table shows only a sub-set of defined "*CompositePhenomenon*", the full set is available by methods described in Sect. 3.2.

CompositePhenomenon	*Phenomenon*
Temperature, Pressure, Humidity	Air Temperature Humidity Barometric Pressure
Surface wind	Wind Speed max Wind Speed Wind Direction
Radiation	Outgoing (reflected) long wave solar radiation Net short wave solar radiation Albedo Incoming short wave solar radiation ... ...
Precipitation	Average Snow Height Rain/Hail
Stream Flow	Volume of Stream flow River water level River flow velocity

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Table 5. Overview on the installed ROMPS and their sensor equipment. The seismometer at Kokomeren is independently installed sharing the VSAT link only.

	BAITIK	TARAGAY	KOKOMEREN	ABRAMOV	MERZBACHER 1 & 2
Altitude	1580 m	3510 m	1470 m	4100 m	3400 m
River basin	Chu	Naryn	Naryn	Vaksh	Aksu
Installation	Dec 2009	Aug 2010	Nov 2010	Aug 2011	Aug 2009
Sensors					
GPS receiver	X	X	X	X	X
Seismometer		X	(X)	planned	X
Wind	X	X	X	X	X
Air pressure/humidity	X	X	X	X	X
4-components net radiation	X	X	X	X	X
Soil moisture and temperature	X	X	X	X	X
Rain gauge	X	X	X	X	X
Air pressure	X	X	X	X	X
Snow pack analyzer	X			X	
Snow height	X			X	
Snow pillow	X				
River discharge	Planned		X		

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Table 6. Station installations planned for 2012 and 2013. All stations will be equipped with standard hydrometeorological sensors and GPS.

	Maidantal	Kamchik Pass	Maidanak	Dupuli	Ayvadzh	Nizhny Pyandzh	Kabul
River basin	Pskem	Akhangaran	Kashkadarya	Zerafshan	Amudarya	Pyandzh	Kabul
Snow pack analyzer	X	X	X				
Snow height	X	X	X				
River discharge	X			X		X	

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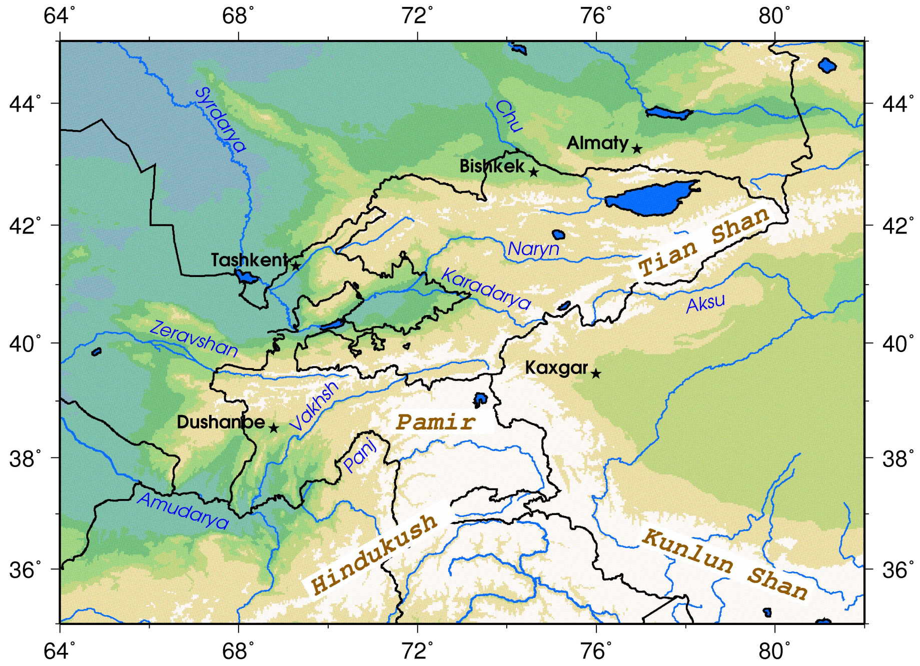

Fig. 1. Geographical setting of Central Asia with its major river systems.

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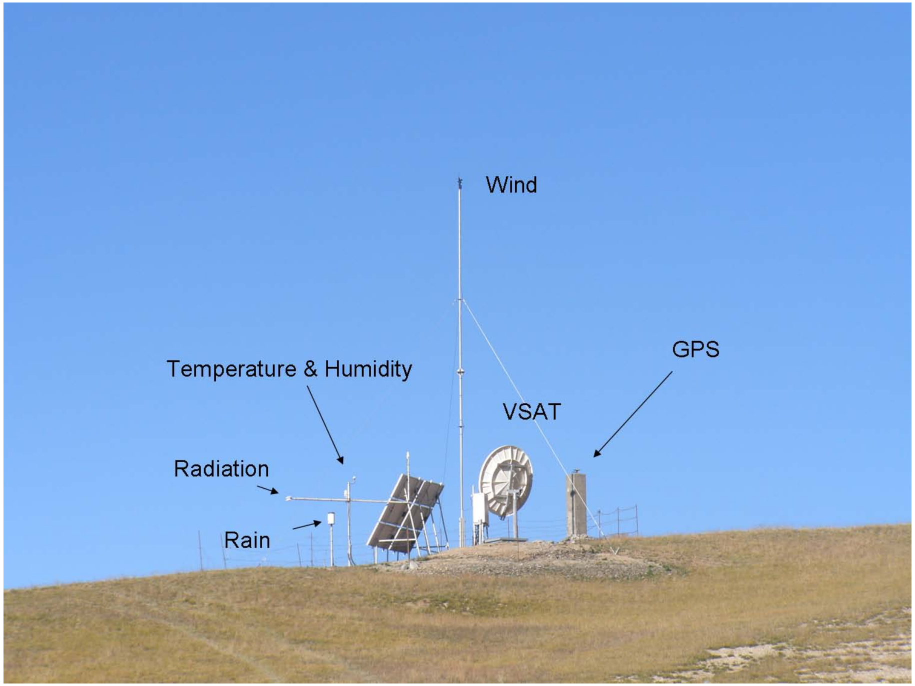

Fig. 2. CAWa station Taragay with a typical sensor setup. The station is powered by solar cells. Sub-surface sensors are not shown.

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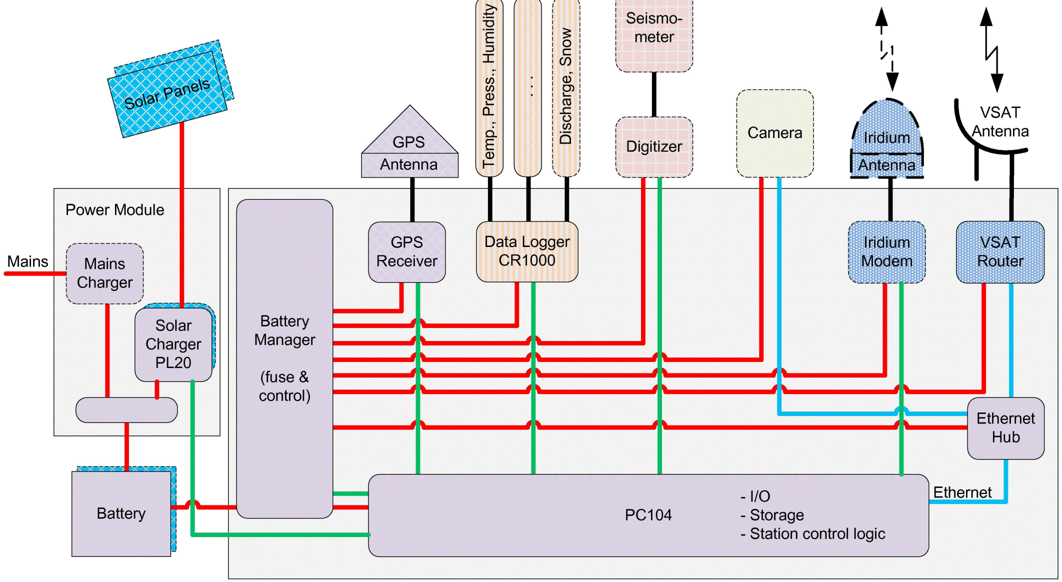

Fig. 3. Schematic ROMPS concept: (red lines) power lines, (green lines) RS232 connections, (blue lines) Ethernet connectors. The Power Module (left) provides 12 V power and power state information. All hardware is connected to and managed by the PC module (PC104 & Battery manager) and dedicated software.

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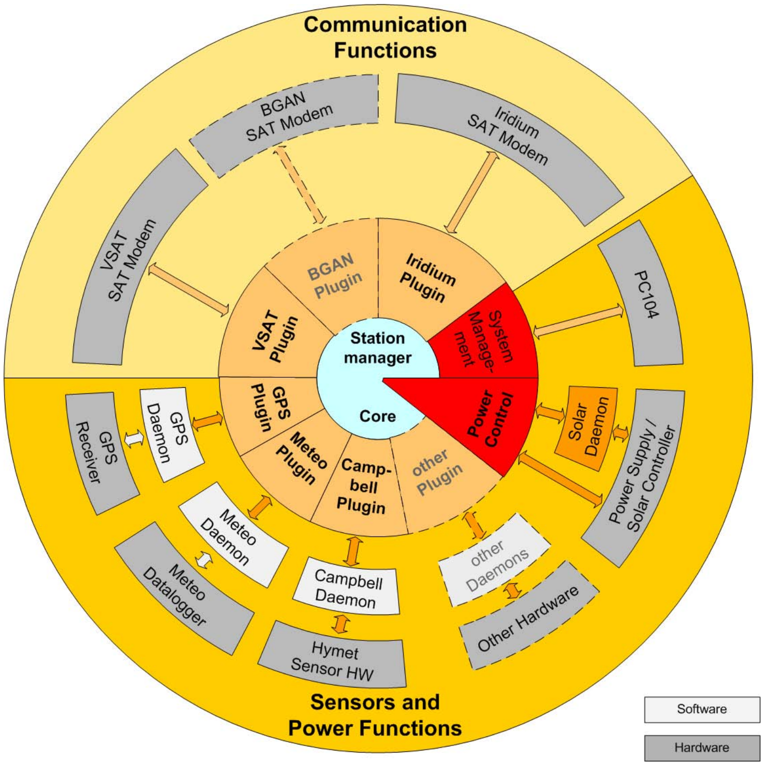

Fig. 4. ROMPS Software concept for the station management. Other hardware and daemons (gray letters) can be integrated (modified after Kloth, 2008).

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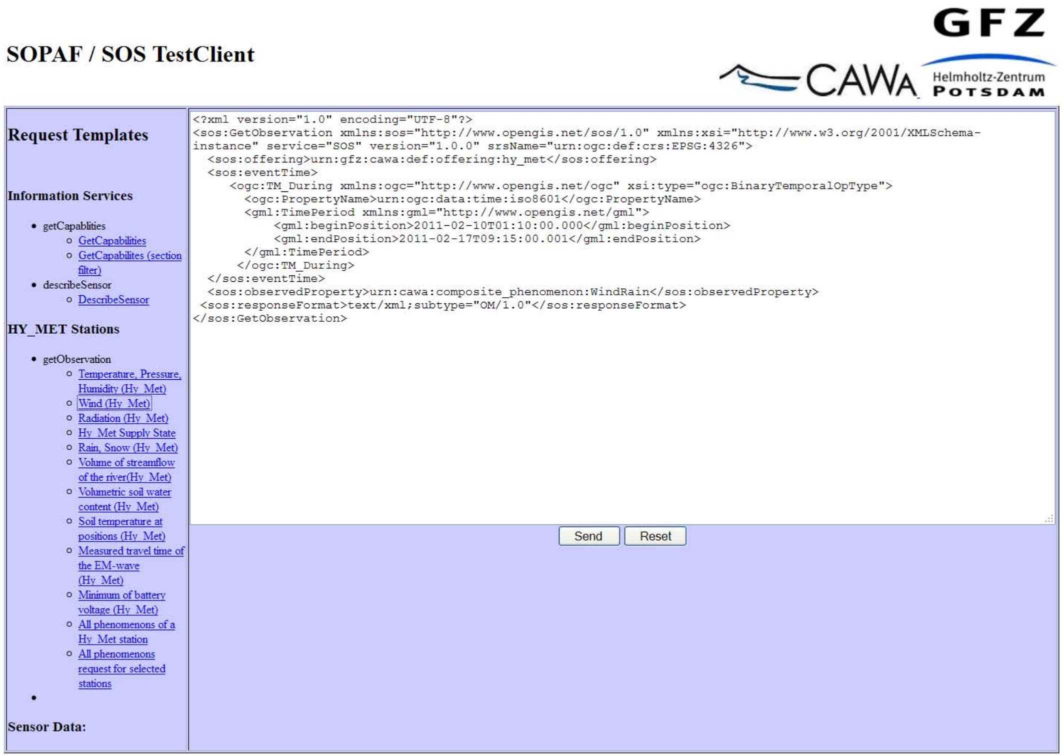

Fig. 5. The SOS Test client, which is designed for writing queries in XML format, contains sample code to support user applications.

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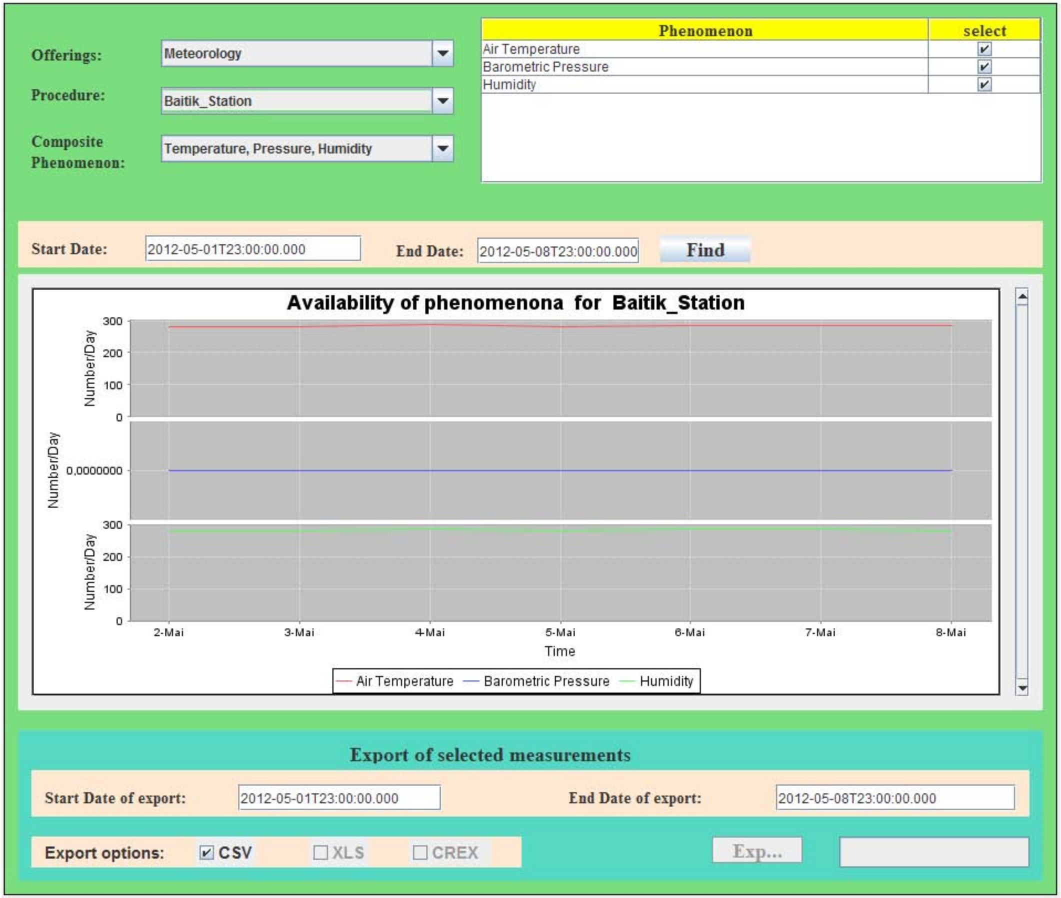

Fig. 6. Export of information from SOPAF. Graphical user interface (GUI) for users who prefer the data in the formats CSV, XLS or CREX.

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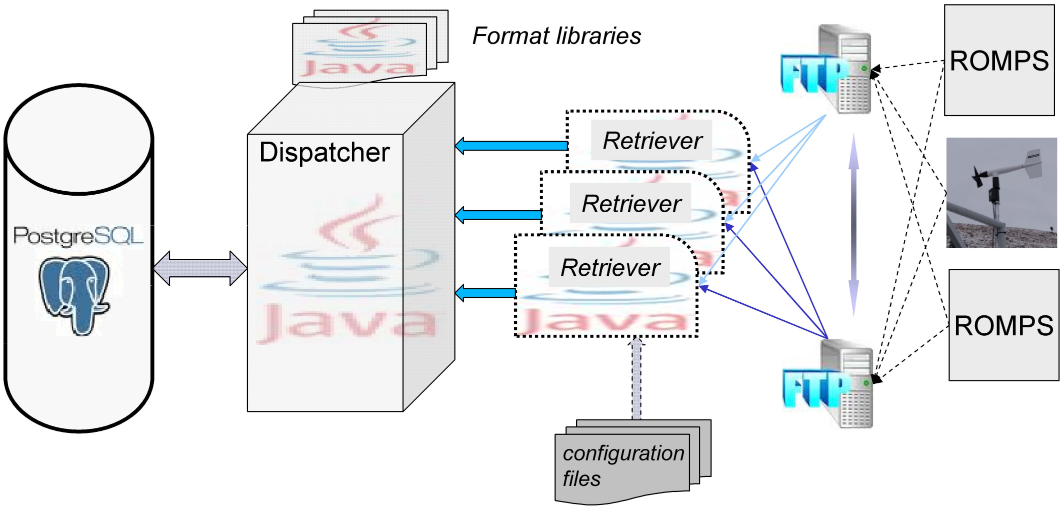

Fig. 7. SOPAF – collection and processing of information. The retrievers are forwarding the newly arrived data. The dispatcher converts the information into the SOS data model using the translation information of the format-library.

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Fig. 8. Central Asia including Afghanistan with the existing and planned installations of ROMPS.

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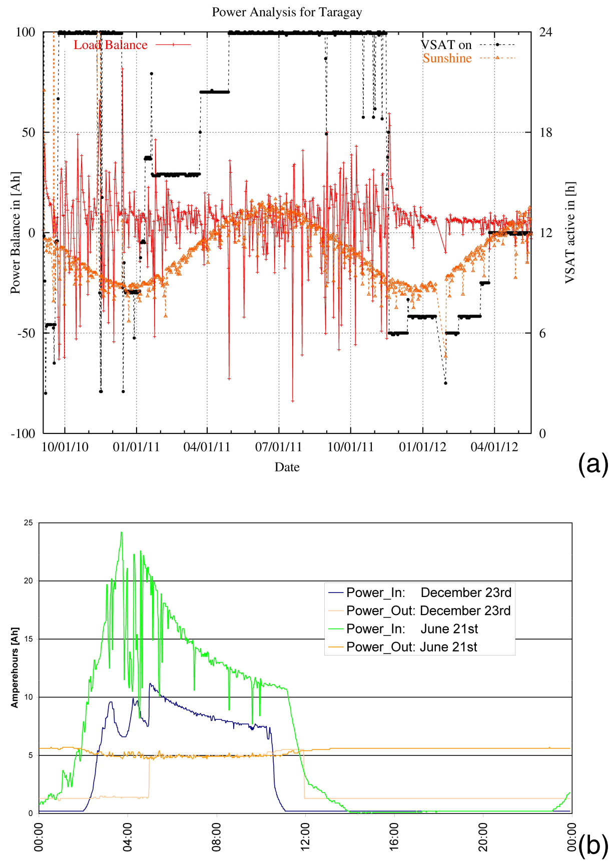

Fig. 9. **(a)** Power balance (red line, left axis) is close to zero. The variability during winter time is related to periods with cloudy skies. The black line indicates VSAT on-times (right axis). The orange line (right axis) shows daily sunshine hours and the grey line (right axis) times, where the input power exceeds current drain. **(b)** Power Charge (green, blue) and Load (orange) at Taragay station for 21 June and 23 December of 2011. The solar input and output is 145 Ah/127 Ah and 70 Ah/58 Ah respectively. For summer times, VSAT connection is maintained for 24 h, while in winter times, the VSAT is available depending on the power level.

Fig. 10. Picture taken from Abramov station (ABRA) Camera #2 (8 February 2012).

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