THE CHALLENGE TO INCREASE THE PERFORMANCE OF AN AWS

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Abstract

For more than 25 years observing systems and applications are developed to design automatic weather stations to provide observational data without any help of human observers. During this period a conclusion was drawn that AWS will have the same performance as the traditional manned weather stations, so begin 1990's the functional specifications on the required performances were equalized. Significant differences remain however, typically for the measurement of present weather. Especially the automatic observation of significant weather phenomena in the vicinity of a station is still a challenge for observation system developers.
To reduce costs many governments stimulate to replace the manned stations by AWS. However, because any observing system is not capable enough to produce all type of weather information in the required format, a number of applications are introduced to increase the performance of AWS in general. Of special interest are the filtering or data-converting algorithms using validation schemes to modify measured data. Such algorithms are usually based on empirical constraints (e.g. precipitation at an air temperature above 5°C will always become liquid, never solid) or climatology (it never snows in summer, so any detection of snow is automatically converted into rain). Also data from lightning and RADAR networks are used for generation of the local AWS bulletins giving the false impression that precipitation or a thunderstorm is observed at the AWS site. As a result the performance of these AWS is increased significantly and experienced to be more reliable from the point of view of the data user. However, this policy is rather doubtful in the eyes of the metrological engineer. Moreover, the applications and algorithms are not well documented nor standardized. Typically, for climatological applications, it will be a hazardous task to investigate or validate the correctness of observational data.
This paper focuses on this issue of ultimate automation and some examples are given of typical impacts of this development.

1 INTRODUCTION

In September 1996, so about 40 years ago, a two-week Technical Conference on Automatic Weather Stations (AWS) was convened by the WMO in Geneva. I presume that this conference is one of the first conferences on AWS during which some 50 papers were presented mainly dealing with performance characteristic of AWS. Moreover a number of optimum requirements were stated to be met by AWS include in the World-Wide Network. When reading the proceedings of this conference (WMO, 1966) it is clear that at that time digital communication for operational practices was at the level of telex communication and most of the instruments had an analog output only. Nevertheless, the technology involved in automatic measurements, data-acquisition, storage and dissemination was already at a remarkable standard, suitable for operational practices. In fact, remote measurements are already from the very past when it became possible to transmit data over telegram lines. So, although AWS has the flavour of new and today's technologies, it was introduced long ago. Experiences with AWS are documented and analysed for many decades providing extended information for researchers and developers in the field of automation of weather observations. Nevertheless, starting the 1990's, AWS are become extremely popular and complete automatic observing systems are introduced replacing the traditional manned stations. Of course reduction of personnel costs and improved reliability may be the driving forces for this

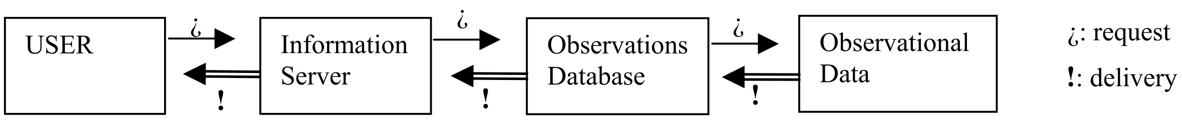
development, but mainly the introduction of new optical observing technologies to replace the visual observations has triggered this trend.
Although these optical and other remote sensing techniques are very promising and useful, the data users are still not very confident on the reliability and usefulness of the reported data. In fact, visual observations, although sometimes expressed in qualitative and subjective expression and not in quantitative variables, are regarded as more reliable. As a result a manned station is considered as with a higher status than an AWS although the required uncertainties of both types of stations are equal. Therefore, because of the many economical and practical benefits of AWS, it's relevant to stimulate the further development of such technologies to make AWS just as reliable as manned stations. For this purpose the increase of the performance of AWS must be well recorded and analysed to find out if the mutation of networks manned stations into networks of AWS is developing well. This development is not only relevant for local users, but also for the new strategic programmes like GEOSS (Global Earth Observation System of Systems). This statement seems to be a rather trivial issue, but in fact we have to consider first the relevance of weather observations within the context of requirements stated by the various disciplines of meteorology and climatology.

2 PRINCIPLES IN WEATHER OBSERVATIONS

Weather observations can be split into two categories:

1. Measurement of required physical quantities
2. Assessment (*e.g.* by visual observations) to recognize the state and development of the atmosphere, and of significant weather.

Meteorological instruments traditionally perform the first category with *in situ* measurements at surface level, but also at various altitudes in the atmosphere. The second category can be regarded as a three dimensional observation, recognizing specific weather *remotely*, although in the vicinity of the station (or observer). Note that not only the actual state is recorded, but data from both categories also contain some predicting elements. From a series of measurements from the first categories a trend can be determined (like pressure tendency), interpretation of data from the second category may gives the actual development of the atmosphere or *e.g.* incoming severe weather.
Although observations are regarded as useful for multi purposes, observational data is user related and not a stand-alone standard product. The following diagram can visualize this best:



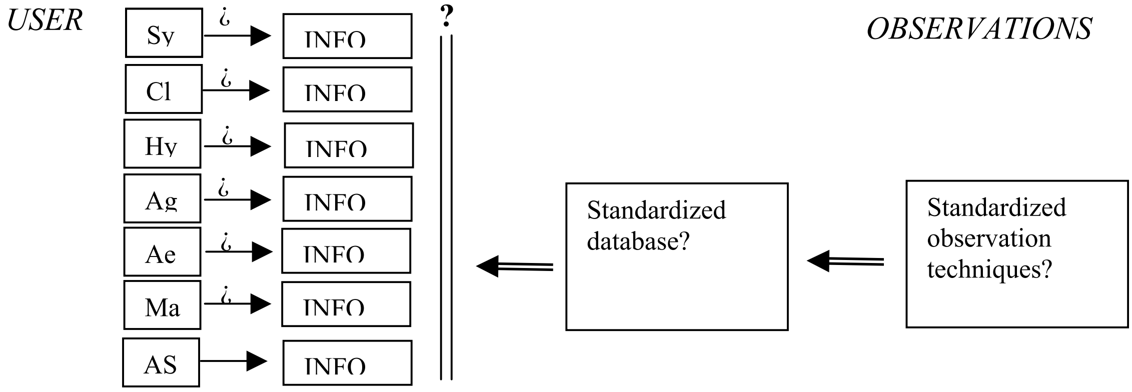
Note that this scheme differs in presentation from the more classical version:

So the user has to specify first the information needs from which secondly the observational requirements can be formulated. Because of the existence of many disciplines in environmental services, there are various sets of functional specifications related to observational data. Roughly, these disciplines are covered by the following seven categories:

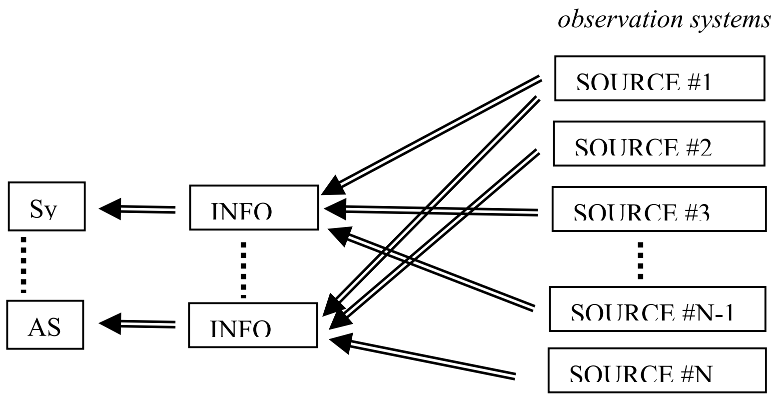
[Sy] Synoptical Meteorology
[Cl] Climatology
[Hy] Hydrology
[Ag] Agro-meteorology
[Ae] Aeronautical meteorology
[Ma] Marine meteorology

[AS] Sciences of the atmosphere

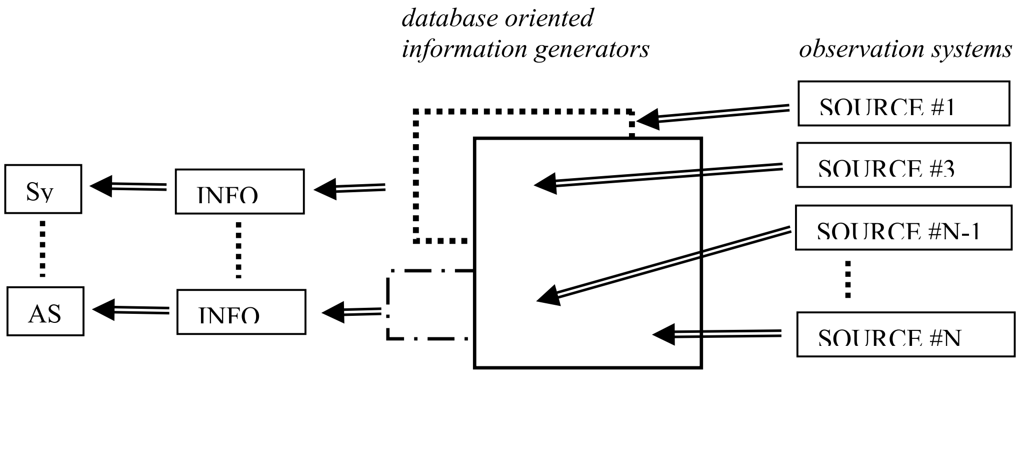
As a result, in general seven sets of requirements are stated:



As visualized in this scheme, the question arises if standardized observation techniques can support all the needs of the users. In other words, is it possible to design such an AWS applicable for multi purposes? In theory a positive answer can be given, but in practice the situation is more complex because observational information is not based on surface observations only. Apart from *in situ* observations in the upper air (*e.g.* radiosonde, AMDAR), data from *remote sensing* technologies are used as well, such as from surface based systems and networks (*e.g.* RADAR, RASS) or from satellites. The latter one has demonstrated clearly its usefulness, especially for quantitative observations of data sparse areas (*e.g.* wind scatterometers). Within the very short future new operational meteorological satellite systems will provide an increasing amount of data related to physical quantities both at surface level and in the upper air. So in practice a variety and in some cases redundant data sources are available to generate the required information. So in fact the following simple diagram can present the use of data from the various sources:



Or, when considering a situation with a more or less integrated environment (the GEOSS style) and information providers using redundant databases:



Considering these schemes and assuming that surface observations, like with AWS can be regarded as one of these data sources it is clear that defining a *standard* AWS is a hazardous exercise. Not only because of the current situation, but also because of the ongoing advances in observation technologies used and of the changing needs of the user community.
May be the wish to define and to design such a standard AWS is too challenging and unwise to see it as a stand alone activity without considering other technological developments. However, all disciplines in meteorology and climatology have stated their own functional requirements on surface observing stations, in particular AWS. These requirements can be found in the WMO Manual on the Global Observing System (WMO-No. 544) for synoptical and aeronautical meteorology and for climatology. Some other WMO Guides and Manuals give requirements on observations as well, like for [Sy] the Guide to Climatological Practices (WMO-No. 100), [Ag] the Guide to Agricultural Meteorological Practices (WMO-No. 134), [Ma] the Guide to Marine Meteorological Services (WMO-No. 471), [Hy] the Guide to Hydrological Practices (WMO-No. 168) and [Ae] Technical Regulations (WMO-No. 49), Volume II. Note that in most of these documents distinction is made between manned and automatic stations. Finally, all these requirements are interpreted into recommendations on how to perform these required observations and published in the WMO Guide to Instruments and Methods of Observation (WMO-No. 8). In this latter document, well known as the CIMO Guide, a collection of all types of observations are presented and acts therefore more or less as a standard document for observations, also for AWS. In paragraph 5 details are given on the development and interpretation of these recommendations in order to propose a standard AWS.

3 CRITICAL ISSUES IN THE DEVELOPMENT OF AWS

At weather stations the majority of observations is based on *in situ* surface and upper air measurements an only a small set on the assessment of the state of the atmosphere. Traditionally, assessment of the state of the atmosphere is performed by 'visual and subjective observations.' Note that measurements are characterized by objective values of physical quantities but visual observations are typical qualitative and quantitative estimates.
Traditionally, at manned stations, the instruments acts as a measurement tool to provide the observer a quantity, which can be corrected and reduced to a nominal value (*e.g.* mercury barometers). At an AWS such instruments are fully automated and the *in situ* measurements are straightforward, trivial operations. This type of automation looks more or less as an ICT project and no change of observing technologies are required or a different method of observation. Nevertheless in line with the introduction of AWS, the design of instruments, its shielding and site locations are changed. For instance, Stevenson screens are replaced by multi-plate screens, mercury barometers are replaced by barometers using sophisticated electrical digital sensors, psychrometers are replaced by electrical hygrometers. Also the layout of the stations are changed reorganizing the position of the sensors. Furthermore, siting of the stations is changed due to the increased freedom to find a suitable location. Apart from development of used techniques and station layout automation has a serious impact on management and maintenance. On many AWS there is only remote control of the performances of the instruments and the state of the terrain. This difference with the traditionally manned stations has a serious impact on preventive and corrective maintenance policy, an impact that is not always well foreseen when introducing AWS. But not only maintenance, also the required regular inspection of the station requires another approach on case of remote, unmanned locations. Nevertheless such bottlenecks can be tackled but requires skilled and experienced personnel.
In fact the great challenge of the introduction of AWS is the automation of visual and subjective observations. It is experienced that reports of such observations from AWS should be critical analyzed and validated with respect to the other quantitative measurements. For the automation of these types of observations some practical problems has to be solved first:

- How to register quantitatively specific weather phenomena on remote distance, like:

- significant phenomena (thunder, obscuration, showers, fog patches or whirls in the vicinity)
- different mixtures of precipitation types and intensities, iclusive freezing, blowing, drifting
- cloudiness: not only coverage and cloud base, but also cloud type like cumulonimbus to indicate convection (*e.g.* CB, CTU)

Reporting such phenomena and the indication of convection are found to be relevant, especially for local weather reports at airfields.

- How to encode all these phenomena:
  - SYNOP w_aw_a table 4680 or the METAR table w'w' is found not to be adequate.
  - It is expressed that dedicated database-oriented bulletins are the only way to find a solution

In order to find a solution WMO organized several meetings focussed on requirements and representation of data from AWS (expert meetings in 1997 and 1999) and established in 2000 an expert team on 'requirements for data from AWS' (ET-AWS), which met every two years and prepared recommendations, especially on code matters but also on quality control issues and metadata. In paragraph 5 some details of these recommendations will be given.

4 TRENDS IN INSTRUMENT DEVELOPMENT.

Apart from the introduction of new techniques, a critical trend in instrument development is observed in the past 20 years. For more than a century many instruments are designed according to a 'classical concept' based on continuous improvements. Such improvements are initiated to increase efficiency, reduce maintenance and to reduce the measurement uncertainty. The main target of such development is to obtain more accurate and reliable results. Typically, NMHS were well equipped with an R&D section on instrument development. The common users (*i.e.* the meteorological service) accept these attainable performances as the *status quo*, assuming that future improvements will be a continuing activity of R&D. Nowadays however, instruments will be manufactured according to *functional specifications* which are recommended as standard guidelines. Techniques, which meet these specifications, do not require further development, so redesign is only initiated by economic reasons. Moreover, new developments and production is carried out mainly by the equipment industry (HMEI). Typically, instrument development at the NMHS is reduced to testing and intercomparison to select the most reliable or cost-friendly solution. As a consequence knowledge and experience on how to design an instrument will reduced too at NMHS. So, it can be expected that knowledge of observation techniques will reduce too in future at those centres. This development will have a serious impact on the feedback from the users, the maintenance personnel to the equipment industry and it can not be predicted what the effect will be on the quality of surface observations and on the redesign of AWS.

5 DEVELOPMENT OF THE STATUS OF AWS.

The WMO Manual on the Global Observing System (WMO-No. 544) indicates for various disciplines a number of sets of variables to be measured by surface weather stations. Typically, the sets for AWS are limited subsets of those for manned stations. Therefore it is clear that in general an AWS will be regarded as to have a lower status than a manned station, although such statement is never expressed. Such statement cannot be valid, because in 1994 it was decided to withdraw the specific table on 'accuracy requirements for AWS for synoptic meteorology' from the CIMO Guide (WMO-No. 8) and a common table was introduced to be used uniformly for all disciplines independent of manned of automatic stations.

It is clear that an AWS acting as principle synoptic or climate station should be regarded as of equal performance and reliability as a traditional manned station, with or without some variables. However, if the common experience of the quality and availability of AWS data is negative with respect to manned stations, then its status will never equal that of a manned station. The major bottlenecks today relevant for this situation are related to the following variables or elements:

- Present and past weather
- Clouds
- Special phenomena
- State of the ground

All these variables are related to the automation of visual observations. A critical constraint here is the fact that the more or less qualitative and subjective observations had to be replaced by reports of physical quantities, which is explained in paragraph 3. This transfer is not only a great challenge for instrument developers of the (reduced) R&D sections, but also for the inexperienced user, who has to interpret another type of information. Nevertheless a report such as 'snow at clear sky' can be explained from this point of view, but gives unacceptable confusion even for the most experienced user. This situation can only be improved if technology research for instrument development is prioritized (see above) or if other currently existing observing technologies are implemented in the information generation process. The second solution is relevant and can be regarded best in the process of integration of observation systems (GEOSS), with a dominant role of satellite-based remote sensing systems.

In order to stimulate R&D for instrument development and in particular for the development of present weather sensors (PWS), the WMO expert meetings, as indicated in par. 3 endorsed that such R&D can only be successful if the functional specifications of these type of measurements (see par. 2) are clearly defined and recommended. A number of detailed requirements are developed by the WMO-CBS expert team on AWS (ET-AWS) and recommendations are presented on the WMO website. These recommendations are referring to.

- Functional specifications for AWS, expressed for all suitable variables (existing or new)
- BUFR template tables
- Quality indicators
- Metadata
- Basic set of variables to be reported by a 'standard AWS for multiple purposes'.

The development of latter issue, *i.e.* defining a standard AWS, should have great advantage because such an AWS should support *e.g.* synoptical, aeronautical, marine and agricultural meteorology and climatology. Networks of these kind of stations will be cost-effective because many disciplines are provided with the same kind and quality of data, which is useful in case of overlapping WMO programmes (*e.g.* like with WWW and GCOS). An example of such a table is given in table 1.

Variables	WMO MANUAL on the Global Observing System (WMO-No. 544)				**STANDARD**
	SYNOP Land Stations	[Fixed] Ocean Weather Stations	Aeronautical meteorological station	Principle climatological station	
Atmospheric Pressure	M A	M A	X [1)]	X	**A**
Pressure tendency & characteristics	[M]	M			**[A]**
Air temperature	M[2)] A	M A	X	X[3)]	**A**
Humidity[5)]	M A	M	X[4)]	X	**A**
Surface wind[6)]	M A	M A	X	X	**A**
Cloud Amount and Type	M	M	X	X	**A**
Extinction profile/Cloud-base	M [A]	M	X	X	**A**
Direction of Cloud movement	[M]				
Weather, Present & Past	M	M	X	X	**A**
State of the Ground	[M]	n/a		X[7)]	**[A]**
Special Phenomena	[M] [A]				
Visibility	M [A]	M	X	X	**A**
Amount of Precipitation	[M] [A]	[A]		X	**A**
Precipitation Yes/No	A	[A]		X	**A**

Variables	WMO MANUAL on the Global Observing System (WMO-No. 544)				STANDARD
	SYNOP Land Stations	[Fixed] Ocean Weather Stations	Aeronautical meteorological station	Principle climatological station	
Intensity of precipitation	[A]				
Soil temperature				X	**A**
Sunshine and/or Solar radiation				X	**A**
Waves		M [A]			**A**[8)]
Sea temperature		M A			**A**[8)]

Explanation	*Notes:*
M = Required for manned stations	1) Also QNH & QFE
[M] = Based on a regional resolution	2) Optional: extreme temperatures
A = Required for automatic stations	3) Inclusive extreme temperatures
[A] = Optional for automatic stations	4) Dewpoint temperature
X = Required	5) Dewpoint temperature and/or RH and air temperature
	6) wind speed and direction
	7) snow cover
	8) sea and coastal stations only

Table 1 Basic set of variables to be reported by the standard AWS for multiple users

6 PERFORMANCE INDICATORS.

Measurements providing variables expressed as physical quantities can relatively easy be specified in terms of measurement uncertainty. So developing statements on requirements is rather straightforward. However, for present weather (PW) observations such a development is far from easy. First of all, the reference for an automatic PW observation is traditionally a visual observation. Such a visual observation is, as stated already, in many cases qualitative and subjective. Intercomparisons of data from independent visual observations learn that the quality of visual observation is rather doubtful or not consistent. As a consequence the interpretation and analysis of data from PWS using visual observations cannot easily be presented in terms of simple objective parameters. Although it is generally stated that the performance of many PWS in combination with sophisticated algorithms is not at the required level, a well-defined quantitative indicator is not available for the use of an objective reference. Moreover it is experienced that it is extremely difficult to define such objective criteria for the evaluation of these performances. Automatic temperature or pressure measurements can relatively easy be compared to a (pseudo) reference or travelling standard. Such a comparison is quite hazardous for variables as present weather, clouds and *etcetera*. Discussions on these performances are very diverse and focus on the more traditional issues of automation typically related to the technology used (*e.g.* on visibility, where differences are discussed between automatic point measurements and the visual remote measurement). Such discussions also focus on types of observations with a high qualitative and subjective impact (*e.g.* type of precipitation: choosing between rain, drizzle, sow or hail and all possible types of their mixtures). It has become popular to evaluate the performance of PW observations using the analysis of so-called contingency tables. In such tables statistics of automatic PWS data are compared with visual observations data. Because such a table cannot be regarded as a suitable performance parameter itself, from these tables a number of parameters can be distilled and regarded as *performance indicators*. Examples of such indicators are:

POD: Probability of Detection: The fraction of reported events with respect to the total number of real events.

FAR: False Alarm Ratio: The fraction of incorrectly reported events with respect to the total number of reported events.

These indicators are clearly defined for a specific target, a parameter to indicate the total performance can be given best by the Equitable Skill Score, or Hanssen-Kuipers Score, to be regarded as a 'likelihood score':

ESS: Equitable Skill Score, defined by the difference of the Probability of Detection and the Probability of False Detection, *i.e.* POD – POFD.

Note however that there does not exist any clear international recommendation on the use of skill scores. Some understanding of the usefulness of such indicators can be given by the following simple example. For this example we have chosen for a precipitation detector, in fact the simplest PWS. Such a sensor detects rather objectively precipitation, which can be compared with the report of an observer to be regarded as the truth or reality. The results of these measurement can statistically be presented by a contingency matrix given in table 2:

		detector: yes	detector: no
reality	yes	**a**	**b**
	no	**c**	**d**

Table 2.

Example of a contingency matrix for a precipitation detector. The values of a, b, c en d indicate the fraction of the reported events, so a + b + c + d = 100%

For this example, where we define that 'event' is for precipitation = yes, we have:

POD = a / (a + b)
FAR = c / (a + c)
ESS = POD – POFD = a / (a + b) – c / (c + d)

Note that for further analysis also the 'bias'-ratio is a relevant value, defined by

BIAS = (a + b) / (a + c),

which is the ratio of the number of detected precipitation and the real number of precipaptation event. Ideally, BIAS should be 100%. In practice this bias ratio can be tuned (or 'adjusted') to become 100%, *i.e.* by tuning the sensitivity of the sensor. Such practice, however, will not work for all types of sensors but for the simplicity of this example the BIAS value is set at 100%. A possible result might be:

		detector: yes	detector: no
reality	yes	**15%**	**5%**
	no	**5%**	**80%**

POD = 75%
FAR = 25%
ESS = 69%

The question now is if these values for POD, FAR and ESS are acceptable or not. Should we require POD = 98%, FAR = 2% and ESS = 98%? This issue becomes quite hazardous if we require such figures for specific critical types of weather or for specific, relevant temperature ranges like -2°C < T < +2°C. On the other hand, if we add a simple temperature sensor to this detector and state that by definition for T < -2°C, w_aw_a = snow, for -2°C < T < +2°C, w_aw_a = mixed, and for T > 2°C, w_aw_a = rain, than we have an ultra-simple and cheap PWS with a relatively high POD, low FAR and acceptable ESS. These kind of tricks are implemented in the algorithmic software of commercial PWS. It is based on empiry, not on actual observations but improves the performance significantly in the eyes of the user. In the eyes of an instrument developer or metrologist this approach is extremely annoying because the performance of the output is improved by fine tuning of the software, not by improving the technology of measurement. Such typical filter is for instance based on the empirical correlation between type of precipitation and air temperature (like in the example above. Other 'performance improvers' are for instance related to:

- Climate constraints ("it never snows in summer, so only rain will be reported")
- Extinction - precipitation relation: Visibility will be adjusted using precipitation intensity measurements
- Clear sky - precipitation relationship: In case of *e.g.* 'snow, but no clouds': Clear sky is changed into overcastted.

The question is if these performance improvers should be accepted. Especially in cases were PWS act as 'black boxes' (when details on the algorithms are not provided by the manufacturer) and metadata is very scarce. So, if we want to improve the performance of AWS, should we focus on tuning the algorithms or try to discover new measurement technologies?

Another issue is the use of alternative sources as input for AWS reports like:

- Data from lightning networks
- Data from a precipitation RADAR network

Using these data special phenomena (*e.g.* for thunderstorm in the vicinity, but also cumulus/turbulence or hail) can be reported as if it was observed at the station. In fact, the question is if such alternative sources may be used for the generation of data that cannot be determined by the systems installed on the AWS site. In principle such additional information is not useful because it is already made available through the primary data link (*i.e.* the RADAR and lightning network consoles). However users, who do not have access to these sources are pleased with these (redundant) additions and regard such service as an improvement.

7 SITING, REPRESENTATIVETY AND NETWORK DESIGN

An interesting advance of AWS is the ability to have more freedom in selecting a remote site. Not only finding a location, which confirms better to siting conditions, but also selecting sites which are more representative for its region. Moreover, when designing a new network, it is easier to distribute the AWS over the country in a more equally spaced manner.

However, this flexibility will stimulate to move stations, which will have a very serious impact on climatology. Although the siting of many climate stations is far from ideal, very long-term data records (some for more than 100 years) are disrupted in case of moving the station to a more representative location. So, any redesign of a multi purpose network requires the acceptance of the climatological community. If a manned climate station will be transferred into an AWS, then it is required to measure in parallel all variables from both types of station for a couple of years to be able to be able to intercompare the old and the new datasets in future. Installing a new AWS on a location away from the old manned station will requires the same effort. Therefore, if AWS is introduced and if the current stations have a poor representativety or the siting conditions are far from ideal and moving the station will become necessary with the next 10 years, then it is recommended to plan already now new sites for AWS. Such a timely planned redesign is experienced to be essential in order to organize and finance the required parallel measurements.

8 LAYOUT OF AN AWS

In many countries the introduction of AWS has also affected the design and layout of the site. In some countries a rather simple constructed observing system is defined as to be the AWS. However, an AWS is more than only the equipment. An automatic station implies not the observing system and its sensors but also the terrain, how it is sited, maintained and protected. Only some examples are published in WMO documents and all for manned stations (see fig. 1). Although the examples are applicable for AWS as well, new constructions are designed to reduce costs. For a number of those new designs it's clear that no great care is taken to avoid any possible artificial influence to the individual measurements, which are caused by the construction, the sensors or other items.

Although the sensors might be well selected, calibrated and adjusted, the local impacts might be significant. Therefore any modification of the layout of a station should be considered seriously. Moreover such a modification should be well documented in the meta-database of the station and in full detail.

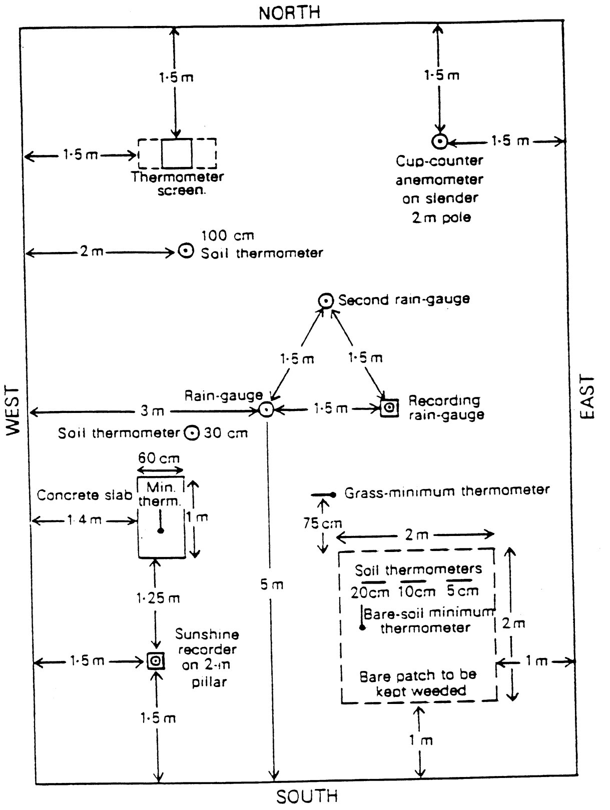


Figure 1 - Sample layout of station

9 CONCLUSIONS

Automatic Weather Stations are developed and introduced many decades ago. The last decade AWS has become more and more the principle weather observing station replacing the manned stations. Although AWS has clearly demonstrated to be able to comply with the stated functional requirements for operational practices, a number of relevant issues remain to be solved to give AWS equal status as a manned station. These issues are related to variables, which are related to the visual or present weather observations. Development in new technologies to improve the situation is limited and there is a trend the use alternative data sources like satellite remote sensing data. Performances are largely improved by cosmetic methods, not by new technologies. Because the performance (or measurement uncertainty) of present weather observations cannot easily be demonstrated by parameters, necessary to show any trend, such parameters should be introduced and used for indicating the functional requirements of AWS. Moreover items like layout, siting and representativity remain relevant issues to be solved to increase the reliability of observations reported by AWS.

References

WMO, 1966: Meteorological Observations from Automatic Weather Stations.World Weather Watch Planning Report No. 10 (WMO, Geneva).