UNIVERSAL UPPER AIR SOUNDING SYSTEM

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1. INTRODUCTION

The earliest automated upper-air sounding systems used RDF wind finding and were able to track qualified radiosondes from multiple manufacturers. Examples include the ART-1 and ART-2 systems employed by the U.S. National Weather Service (NWS). By being able to fly sondes from multiple manufacturers, the NWS has been able to purchase disposables using competitive auctions. Competition has encouraged manufacturers to offer the best prices and has stimulated product innovation.

When the NWS decided to replace the ART ground systems, a key design specification was the ability to fly multiple sondes from competing manufacturers. This would allow the NWS to continue purchasing disposables through competitive auctions.

The requirement to fly multiple sondes marks a reversal from the trend that has been in place since the early 1990s when radiotheodolites were largely displaced by NAVAID systems. With the introduction of the first OMEGA systems, ground stations became integrated with radiosondes made by the same vendor. Multi-sonde compatibility disappeared and operators were faced with single-source suppliers without competitive pressures.

As the variety of NAVAID systems increased (OMEGA, Loran-C, coded/uncoded GPS) disposables became even more linked to the accompanying ground stations. After the initial ground station competition, there was little motivation for manufacturers to offer low prices for disposables - or to improve product performance. This led to conditions where operators were paying high prices for products with high failure rates.

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Operators were also exposed to situations where manufacturers discontinued the only compatible radiosondes, making high cost ground stations instantly obsolete (the AIR IS-4A being one example). This forced operators to make costly ground equipment upgrades ahead of schedule.

2. THE UNIVERSAL SYSTEM

In 1999, International Met Systems (InterMet) was awarded a contract to design and build the Telemetry Receiving System (TRS) to replace the ART systems. The resulting IMS-2000 fulfilled all NWS specifications including the requirement for multi-sonde compatibility. The ground station is currently being used with the Sippican Mark IIA and the InterMet model 3010 radiosondes. A new round of qualifications is underway which is expected to see a new InterMet sonde (the iMet 1) and a version of the Vaisala RS92 qualified for use along with the Mark IIA.

After completion of the IMS-2000, InterMet adapted the multi-sonde capability to its existing IMS-1500 radiotheodolite. The 1500 is currently being used at 20 synoptic sites with Sippican Mark II and B2 radiosondes, as well as the IMD-Mk IV manufactured by the India Meteorological Department. The 1500 is also capable of flying the Sippican Mark IIA and the InterMet 3010. Figure 1 shows the IMS-2000 and the IMS-1500 systems. The 2000 is a 2-meter, high gain system designed for fixed installations within a radome. The 1500 is a smaller, lower gain system with a 1.2-meter dish and is designed for portable or fixed installations.

In 2003, InterMet introduced the multi-mode IMS-1600, which integrates 403 MHz GPS capabilities with 1680 MHz RDF. This system was initially developed for military use with the objective of providing complete flexibility for changing field conditions. In 2004, an IMS-1600 was installed for synoptic use in Dar es Salaam, Tanzania under the auspices of the WMO. This system will be a component of the Global Upper Air Network (GUAN).

Figure 1: IMS-2000 and 1500

For purposes of discussion, an upper air sounding system consists of a radiosonde for making PTU and wind measurement, a ground based antenna for receiving data from the radiosonde, and a system computer for controlling the antenna and providing reports and data outputs in various formats. As defined by InterMet, a *universal system* is an upper air sounding system that can use radiosondes from multiple manufacturers. Two other terms also need to be defined to avoid confusion. A dual-mode system is one that can operate in both RDF and GPS wind finding modes. The IMS-1500 and 2000 both have this capability. A multi-mode system is one that operates in both 1680 MHz RDF and 403 MHz GPS modes. The IMS 1600 falls into this category. In this paper, we will be restricting discussion to the universal system, with references to the other modes where appropriate.

The purpose of this paper is to describe the technical challenges of implementing the universal system concept and to discuss the benefits and drawbacks of this approach. The central question is whether universal RDF systems can provide high quality met data at a meaningfully lower life-cycle cost than the GPS systems widely in use.

3. TECHNICAL ISSUES

An upper air sounding system performs four distinct functions:

- Sonde tracking
- Telemetry reception and decoding
- PTU/Wind data processing
- Report generation

Each of these will be discussed below.

<u>Sonde Tracking</u>

The InterMet radiotheodolites use solid state scanners to track radiosondes transmitting in the 1680 MHz meteorological band. The 1500 scanner is vertically polarized while the 2000 uses left-hand circular polarization. Gain and range depend on dish size, with the 2000 achieving 26 dB and a range of up to 300-Km (22dB and 250 Km for the 1500).

Radiosonde transmitters vary widely in the stability of the carrier signal tracked by the antenna. Older designs such as the IMD MK-IV have free running oscillators with relatively poor control over signal stability and relatively high bandwidth requirements. More modern sondes have crystal controlled oscillators that are very efficient and require much less tracking bandwidth.

In order to track sondes with widely different transmitter characteristics, InterMet developed a software controlled digital receiver. When tracking the IMD-Mk IV, the receiver is set to its maximum bandwidth of 1,000 kHz. When used with a more efficient transmitter, the bandwidth is narrowed to as little as 50 kHz to increase performance and gain. This allows the InterMet theodolites to track virtually every 1680 MHz sonde currently being built.

<u>Telemetry Reception & Decoding</u>

Every sonde uses a unique methodology for encoding PTU data before transmission. This coded data stream is passed from the antenna's receiver to a decoder, or signal processing system (SPS). The SPS is a proprietary device that decodes the PTU data on the ground. Most modern decoders consist of single board computers with onboard power supplies and flash memories. They can be free standing or rack mounted.

For a radiosonde to be compatible with the universal systems, the inputs and outputs of the decoder must conform to the requirements of the tracking antenna. As long as these requirements are met, the only hardware required to introduce a new radiosonde is the appropriate decoder.

Portability of the SPS is a critical requirement for the universal concept since it allows the manufacturer to retain control over proprietary methodologies and ensures that the sonde will produce the specified PTU output regardless of the system used to receive the telemetry. The sonde coding and decoding remains a closed system under control of the manufacturer that is indifferent to the antenna used to receive the data and calculate winds.

In a competitive market, manufacturers could provide decoders in a variety of ways including leases, outright sales or loans with the cost included in the sonde price. For example, if an operator purchased sondes for a 12-month period, the manufacturer would lend or lease the decoder for the same interval. If a new sonde was purchased for the next annual period, the decoder would be returned to the manufacturer.

PTU/Wind Data Processing

Each sonde has its own requirements for data corrections and smoothing in order to produce PTU data that meets the accuracy requirements specified by the manufacturer. The most common correction is for solar heating of the temperature sensor during daylight flights. Infrared corrections for day and night flights may also be required. Every sensor has unique solar and infrared correction algorithms that must be applied in either the SPS or the operating system. Although it would be desirable to have this happen within the proprietary confines of the SPS, this has not been done up till now because today's SPSs do not have the information needed to determine if the corrections are needed (e.g., the date, time of day, station coordinates). Since today's SPS are "dumb" and have no ability to communicate interactively with the system computer, there is no way to pass the necessary data or commands.

Similarly, a sonde's PTU sensors may have proprietary functions to smooth the data or make other corrections. This information must be included in the system computer so it can be called up when the sonde is flown.

To protect proprietary information, the SPS could include the solar/infrared corrections as well as any other corrections and smoothing (e.g., wind) if the system computer is designed to provide the required information to the SPS. There is no technical reason why data smoothing and correction cannot be accomplished in the system computer or the SPS. The question relates more to proprietary concerns where manufacturers may hesitate to disclose techniques used to process raw data.

Report Generation

The creation of standard met messages, graphic outputs, etc., is well defined and relatively simple. Once the PTU data is decoded and processed, there are no longer any sonde-specific aspects and the information can be consistently reported. Data editing can also be performed on the output of any sonde.

4. OPERATIONAL ISSUES

There are a number of operational issues that need to be considered to be sure a universal system can be used effectively:

- Calibration coefficient input
- Transmitter frequency control
- Sonde initialization and baselining
- Data quality assessment and adjustments
- Ease of use

Calibration Coefficient Input

Every radiosonde has its own method for transferring calibration coefficients to the SPS. These methodologies have varied widely and are not a trivial issue.

The Sippican Mark II passes coefficients in the transmitted data stream with no operator input required. The B2 uses 5 1/4" floppy disks, which are obsolete and require hard-to-find disk drives in the system computer. The IMD MK-IV uses 3 ½" floppies or manual input of up to 350 pressure coefficients. The Vaisala RS80 uses a proprietary paper tape that is also difficult to obtain.

InterMet has successfully adapted to three of the methods described above and we see no reason why this will present problems in the future. Ideally, sonde manufacturers would adopt a standard method using the transmitted data stream to eliminate the need for special hardware. Cooperation between sonde manufacturers and InterMet has prevented problems in the past.

Transmitter Frequency Control

In order to cope with interference within the meteorological frequency band, radiosondes need to be able to tune their frequencies within the band. This can be accomplished mechanically or through software control.

InterMet and Sippican sondes use mechanical methods for setting frequencies. These vary from a potentiometer in the Mark II to dip switches in the InterMet 3010 and cut wires in the Mark IIA. These methods require no involvement of the ground station and are ideal for the universal system.

Most GPS sondes currently in use (Modem M2K2, Vaisala RS92, Graw DFM97) employ “umbilical cords” to program their transmitter frequencies, to calibrate the sensors, and to enter pre-flight sensor coefficients. This methodology is not currently in use for 1680 RDF sondes. This method is not optimal for the universal approach but could be accommodated using a USB port on the system computer and sonde-specific software. Again, the essential factor would be cooperation between the manufacturers.

Sonde Initialization and Baselining

Every sonde has different requirements for initialization before flight. This is both a training issue and a technical one. The key distinction is whether the PTU sensors need to be calibrated prior to flight.

NWS specifications for sondes to be flown as part of the Radiosonde Replacement System (IMS-2000) require that temperature and humidity sensors be stable enough not to require calibration before flight (Sippican Mark IIA, InterMet 3010 and iMet 1). Other sondes (Modem M2K2 and Vaisala models) require single point calibration of temperature and humidity using calibrated ground sensors.

All sondes with discreet pressure sensors require calibration with a reference at the release point. This has not presented any problems in the past since all upper air stations have calibrated barometric pressure sensors that can be used for reference. No special device is required and the adjustment is made through software in the system computer.

Temperature and humidity sensors are more problematic since accurate calibration requires a controlled environment with a stable airflow. Vaisala and Modem both offer such calibration boxes as options (Modem) or requirements (Vaisala). Failure to accurately calibrate pre-launch will compromise the flight data.

Data Quality Assessment and Adjustments

At the operational level, data quality assessments are no different for RDF systems than GPS and will depend on the experience and training of local observers. A bigger question concerns the impact on time series databases of what could potentially be annual changes in radiosondes.

Climatologists will always prefer the use of single sonde models for extend periods of time to eliminate bias errors in their models. If one of the reasons for adopting the universal system is to encourage competition in sonde selection, continuity will necessarily suffer. The question is whether sonde biases are adequately understood to make the necessary corrections when models are changed at a particular site. The sonde designation is included in the standard met messages so there should not be any confusion about which correction needs to be made. Further discussion of this important topic is beyond the scope of this paper.

Ease of Use

With the widespread acceptance of NAVAID systems, operators have grown accustomed to the ease of release and forget flight operations. Although InterMet’s radiotheodolites are highly automated, they require adequate operator training to capture the sonde at release. Radiotheodolite systems have more parts than comparable NAVAID installations and require slightly more detailed maintenance.

InterMet’s experience with ten synoptic sites in the Caribbean has shown that operators quickly grasp the technical aspects of flight operations. Since we began installing systems in 1997, we have encountered no ongoing flight operations problems and are confident this is not a significant issue.

The IMS-1500 is a mature system that requires very little maintenance. The C release includes extensive built-in-test functions that allow operators to quickly isolate faults to the individual LRU. When necessary, spares are dispatched from either Cape Town, South Africa or Grand Rapids, U.S. to replace failed components. Field experience has shown that the 1500 will operate for extended periods with no electronic or mechanical failures. InterMet also offers fixed-price extended maintenance contracts to eliminate unexpected costs.

5. RDF WIND FINDING

For the universal system concept to be valid, the RDF antennas must consistently deliver high quality measurements of wind speed and wind direction. Accurate winds are one of the selling points of GPS systems. The question here is how do RDF winds compare, and if there is a degree of diminished performance, what is an acceptable tradeoff for the economic benefits of reduced operating costs?

The most noted weakness of RDF systems is the difficulty of generating accurate winds at low tracking angles. Although this is a genuine concern, the potential benefits of the universal approach will be most realized on days when light upper air winds are expected and low angle tracking is unnecessary.

Measuring wind accuracy presents numerous challenges due to the difficulty of obtaining reliable references. The most commonly used test is to track a sonde with high accuracy radar. Dual flights of GPS and RDF sondes are another option that is simpler and less costly to execute. The ability of InterMet radiotheodolites to simultaneously track the same radiosonde in both GPS and RDF modes offers a third option that eliminates many of the measurement errors found in the other two methodologies.

For the purposes of this paper, we will use IMS-2000 (TRS) dual-mode GPS/RDF data. Comparison flights executed in Dar es Salaam during October 2004 by the UK Met Office working under contract for the WMO will be used when the data becomes available.

6. DUAL-MODE COMPARISON

For accurate wind calculations, the accuracy requirement for the azimuth and elevation angles is 0.2 degrees RMS. Figures 3 and 4 show typical TRS measured azimuth and elevation angles on a flight overlaid on the calculated angles from the GPS data. The slightly noisy curves are the IMS-2000 (TRS) measured angles. Because of the high accuracy of the GPS (5 m), it can be used as "truth" when calculating pointing angles. The azimuth mean error is -0.1 deg and the standard deviation is 0.1 deg. The elevation mean error is 0.0 deg and the standard deviation is 0.1 deg. The GPS measurements were used for boresighting the TRS, resulting in the small mean errors.

The major contributor to the wind error is an error in the measurement of the elevation angle, especially at low elevation angles. At elevation angles below 18-20 degrees the wind accuracy begins to degrade below that shown in the plots. Good accuracy is provided down to 10 degrees of elevation.

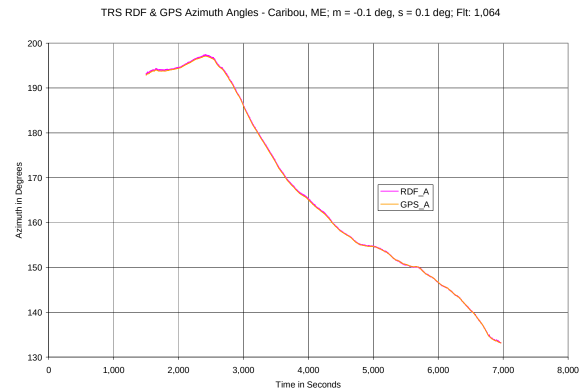

Figure 2 TRS Azimuth Pointing Error

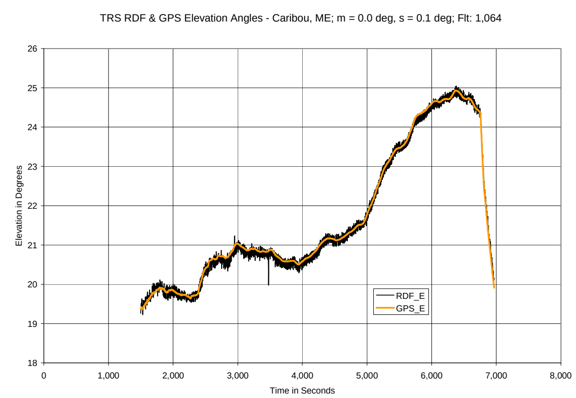

Figure 3 TRS Elevation Pointing Error

7. OPERATING COST COMPARISON

In the sections above we described the technical challenges of applying the universal system concept at synoptic sites. To determine whether the additional effort of using RDF systems is justified, we must estimate the potential cost savings over dedicated GPS systems.

The basic cost model is shown in Table 1. This looks at factors that differentiate RDF (1680) from GPS (403) systems and do not include costs that are the same regardless of which system is used (balloons, lifting gas, personnel). The model looks at fixed costs calculated on an annual basis and variable costs depending on the number of sondes flown each year.

Table 1: Cost Model

Description	Range
10 yr. Straight line depreciation of initial capital cost	$5K (GPS) $10K (RDF)
Maintenance at 2.5% of orig. cost per year	$875 (GPS) $2,500 (RDF)
Sonde cost differential (premium of GPS over RDF)	$50 to $100
Flights per year	365 or 730

From this starting point, fixed and variable costs are calculated as shown in Tables 2 and 3.

Table 2: Fixed Costs

Description	RDF	GPS
Original Cost	$ 100K	$ 50K
Years Deprec.	10	10
Annual Maint.	2.5%	2.5%
Total	**$ 12,500**	**$ 6,250**

Table 3: Variable Costs

Description	RDF	GPS
Sonde Cost	$ 90	$ 160
$/yr – 365 flts/yr	32,850	58,400
$/yr – 730 flts/yr	65,700	116,800

Adding the fixed and variable costs gives the total costs for RDF vs. GPS systems on an annual and per-flight basis (see Table 4).

Table 5 calculates the RDF cost savings in annual, per-flight and life cycle terms. The net benefit is 30% for daily flights, 37% for twice daily.

Based on these simple calculations, the RDF approach appears to offer a significant cost saving on both annual and life cycle bases.

Table 4: Total Cost

Description	RDF		GPS	
	Total $	$/Flt	Total $	$/Flt
$/yr – 365 flts/yr	$ 45,350	$ 124	$ 64,650	$ 177
$/yr – 730 flts/yr	78,200	107	123,050	169

Table 5: Annual Savings, RDF vs. GPS

Description	Total $	$/Flt	%	10 Yr Life
$/yr – 365 flts/yr	$ 19,300	$ 53	30%	$ 193,000
$/yr – 730 flts/yr	44,850	62	37%	448,500

8. CONCLUSIONS

We have shown that there are significant cost savings available from the use of universal RDF systems in synoptic locations. The critical performance element of wind finding accuracy is within acceptable bounds. Operational support requirements are slightly greater than for comparable NAVAID systems but have not proven to be a problem in existing locations.

Technical issues arising from the use of multiple sondes and the lack of consistent methods for calibration and data transfers are an important consideration but do not present any significant obstacles to successful installations. Cooperation between manufacturers can act to minimize these issues in the future.

In summary, we believe that universal RDF systems can deliver high quality synoptic data. There are a number of trade-offs with NAVAID designs but they are adequately compensated for by lower operating costs.