Challenges of downsizing (Development of micro radiosonde iMS-100)

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ABSTRACT

Routine radiosonde soundings twice a day in the world have been providing with long-term and highly accurate data in the upper-air observation. Recently some operational stations have reduced observation frequency to once a day or discontinued due mainly to budgetary restrictions. In addition to meet performance standards that have been established by WMO, Easy operation, Total (initial and running) cost reduction, and enhanced Safety are pressing issues for the valuable and sustainable upper-air observation.

We developed the world lightest and smallest radiosonde “iMS-100” (less than 40g including a battery) to solve the above issues. The lightest iMS-100 decreases risks when it falls on ground after the balloon burst. It can fall-down quite safely even without a parachute because of the slow fall velocity. The lightweight also helps reduce annual gas consumption by ~30% for one station. Since the maximum reachable height depends on the size of the balloon, the amount of gas, and the total package weight, the lightest iMS-100 package can reach 100 hPa pressure level with even small 100 g balloon.

Downsizing of radiosonde (iMS-100) also results in higher measurement performance. One is to reduce adverse thermal effect influenced by radiosonde box since the volume of radiosonde package has been decreased by 70% from that of RS-11G (our previous model). Second, pendulum motions of sonde package are reduced because the lightest-smallest package smoothly rides on the wind. Therefore, micro iMS-100 can better capture “in-situ air” in terms of temperature and winds. Besides, new relative humidity sensor mounted with iMS-100 has been developed to meet an increasing requirement for accuracy of humidity measurement. The quicker response time is within 3 seconds at -40 deg C and about 20 seconds at -60 dec C, respectively, which enables more accurate humidity measurement in the troposphere.

1 Introduction

Routine radiosonde soundings twice a day in the world have been providing with long-term and highly accurate data in the upper-air observation in order to collect fundamental data for weather forecast and air craft operation. Approximately 850 upper air stations are registered in WMO, but recently, the number of station has decreased to approx. 700 due mainly to budgetary restriction. Some operational stations have reduced observation frequency to once a day or discontinued operation because of budgetary cut-back due to political and economic reasons in addition to the recent technical improvements in other observation methods such as satellite and numerical simulations.

Even in Japan, two stations for upper air observation stopped operation in 2008 due to budgetary reasons. After Tohoku earthquake and tsunami in March 2011, the national budget for upper air observation was significantly reduced since part of budget was divided to reconstruction of Tohoku disaster, Japan Meteorological Agency has been forced to take measures, such as changing the procurement method, etc. to maintain the required level of sounding operation.

Reduction of such required sounding quality must be avoided on account of the budgets, which is a world common issue for Bureau of Meteorology and equipment manufacturer to solve.

To achieve sustainable upper sounding network, we need not only advanced sensing technology against other observation methods, such as weather radar, but also cost savings for facility and operation including reduction of man-hours and consumables (balloon and gas).

Meisei, with an endeavor to resolve this issue, developed the world lightest-smallest radiosonde, iMS-100 (Fig. 1). In this report, our preliminary evaluation of downsizing advantages and each sensing performances are described.

Figure 1: Outlook of micro sonde iMS-100

2 Development of iMS-100

Radiosonde has been traditionally designed to save size and weight. But these design approaches always take technical performance requirements as the first priority and the downsizing was considered as the second priority. Also balloon size and gas amount are easily chosen as necessary based on radiosonde weight and reachable altitude. Therefore, active approaches for downsizing have not been actively challenged.

In Japan, where housings and transportation facilities are so crowded, impact of radiosonde falling down after balloon burst needs particular attentions. Japan Meteorological Agency has focused on safety measures such as pipe separator and parachute inside balloon. In summer when westerlies weakened, launched radiosonde frequently falls in built up urban area, which causes damage to the houses and transportation facilities every year because safety method to minimize such risks is only left to the uncertain parachute system. Under the circumstances, Meisei has continued to develop the downsizing of radiosonde. The world lightest radiosonde RS-11G of 85g at that time was developed in 2011.

At the same time, global shortage of helium gas occurred due to shutdown of helium plant in North America. Meisei reaffirms that merits of downsizing is not only safety for lives and property but also secondary effects like gas saving, etc., and started to develop further remarkable miniaturization of radiosonde, iMS-100.

2.1 Design of iMS-100

iMS-100 adopted one lithium battery (CR-123), chipped GPS antenna, and the transmitter, which can reduce weight to below 40g. Table 1 represents the size, volume, weight, and battery of iMS-100 compared with RS-06G and RS-11G.

Table 1 : Geometory of Meisei sondes

	iMS-100	RS-06G	RS-11G
Size	55 X 53 X 131 mm	88 X 98 X 155 mm	67 X 86 X 154 mm
Volume	262 cm^3	1119 cm^3	712 cm^3
Weight	38 g	150 g	85 g
Battery	CR-123(3.0 V) x 1	AA (1.5 V)x 2	CR-123 (3.0 V)x 1

The downsizing of radiosonde makes connection operability difficult, but the problem is solved by using wireless infrared technology (IrDA). As shown in Figure 2, iMS-100 simply consists of sensor boom, main board and battery.

Furthermore, the upper side of radiosonde package is designed roundly to minimize thermal flux (refer to Shimizu and Hasebe (2010)) from the package box itself, which reduces the adverse effect to temperature sensor. 2010 WMO intercomparison in China indicated that the humidity sensor of RS-06G could not detect available data due to slow time constant in the Upper Troposphere and Lower Stratosphere (UTLS). A new humidity sensor for iMS-100 has been developed to accurately measure humidity in UTLS and even in further lower temperature environment. Results of laboratory experiments and field evaluation are shown in Chapter 4.

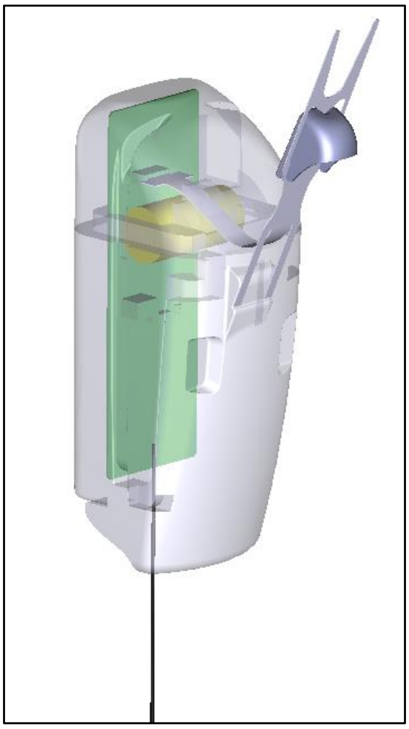

Figure 2 : Layout of internal components

3 Advantage of downsizing

3.1 Reduction of gases and smaller balloon

First merit of downsizing is gas saving. Table 2 shows the reachable pressure level and gas consumption quantity when iMS-100 is launched with 1200g, 600g, 350g, and 100g balloons, respectively. For comparison, those with 150g and 250g radiosondes are also described in table 2. With the big balloon, the downsizing doesn't make big difference in the reachable level and the gas saving because the weight ratio of radiosonde against the balloon is low. On the other hand, with the small balloons, the savings are quite remarkable. As can be seen from the table 2, only iMS-100 is expected to reach 100 hPa pressure level (FM 35 TEMP A and B) with even small 100g balloon. Also, iMS-100 is able to save annual gas consumption cost equivalent to 40 cyl./yr. compared with that of 250 g radiosonde.

Table 2: Reachable pressure level and gas consumption quantity

		1200g balloon	600g balloon	350g balloon	100g balloon
Burst pressure	iMS-100	6.4 hPa	10.4 hPa	19.0 hPa	90.8 hPa
	150g sonde	6.8 hPa	11.5 hPa	22.0 hPa	118.8 hPa
	250g sonde	7.2 hPa	12.5 hPa	24.7 hPa	142.5 hPa
Amount of Gas (He)	iMS-100	2.33 m^3	1.47 m^3	1.08 m^3	0.65 m^3
	150g sonde	2.48 m^3	1.64 m^3	1.26 m^3	0.85 m^3
	250g sonde	2.61 m^3	1.78 m^3	1.02 m^3	1.02 m^3

Figure 3 shows the sounding profile of iMS-100 launched with 100 g balloon, which indicates that iMS-100 can ascend above 100 hPa level.

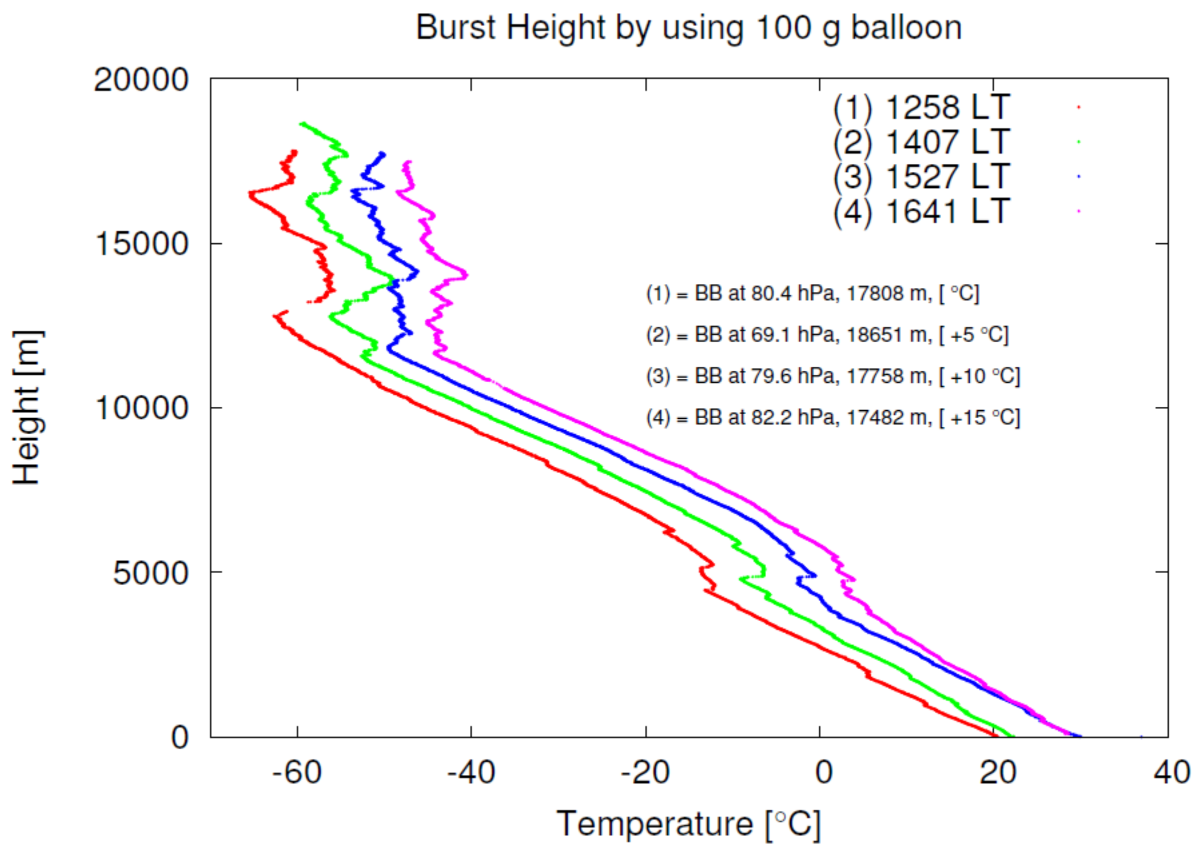

Figure 3: Sounding profile of iMS-100 launched with 100 g balloon at Moriya, Japan.

3.2 Safety launching and landing

Second, the downsizing of iMS-100 also improves safety. Launch of iMS-100 with small balloon has more advantage in safety over the launch with large balloon especially in strong winds due to smaller balloon diameter. Figure 4 presents the impact force of various radiosonde calculated by JMA (Kizu, 2014).

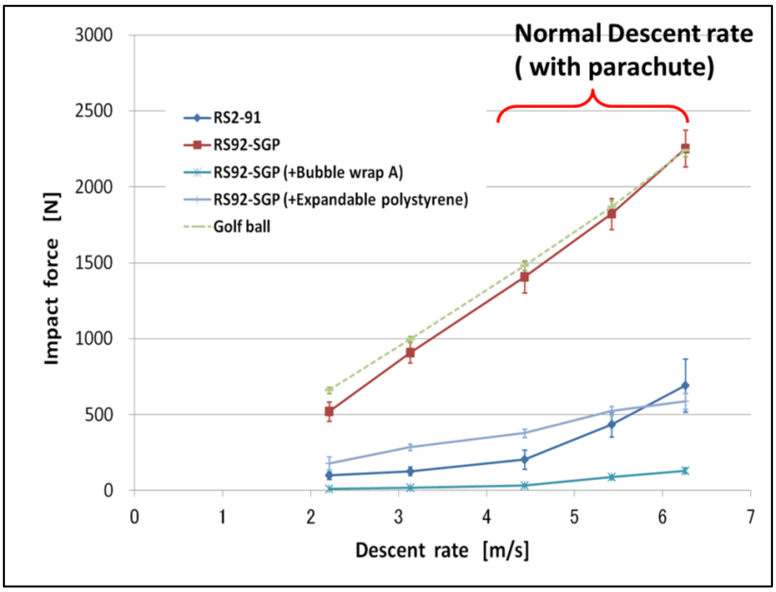

Figure 4: Impact force during radiosonde falling down reprinted from Kizu (2014)

iMS-100 is considered safe enough even without parachute in comparison with conventional radiosonde since the fall velocity averages 7.8 m/s e 0.8 m (N=20: 1 sigma) due to the large air resistance against the sonde weight itself. According to the calculation by the following JMA equation (JMA 2014),

$$F(N) = \frac{mV^2}{L}, \tag{1}$$

where V and d mean terminal velocity and buffer thickness respectively, the maximum impact force of iMS-100 is about 330 N. This impact force without parachute is at least one order of magnitude smaller than that of conventional radiosonde with parachute, which is calculated by the JMA equation 1.

4 Performances

4.1 Wind

Radiosonde is able to measure the horizontal wind by ascending balloon moves riding on the wind. However, since it is suspended from a balloon, combined data of sonde package pendulum motions and real air motion of the balloon is calculated by the GPS. Then, the combined data are normally filtered to remove the pendulum cycle. This period of pendulum motions is known to be defined by the suspension length. The ideal pendulum motion is defined by

$$\mathrm{m}\frac{d^2x}{dt^2} = -\frac{mg}{L}x. \tag{2}$$

Here, m and L are the mass (kg) and the suspension length (m), respectively. Actual radiosonde reduces the fall speed due to the air resistance depending on the velocity (see equation 3 and 4), where k is the drag coefficient, and Re is the Reynolds number.

$$\mathrm{m}\frac{d^2x}{dt^2} = -\frac{mg}{L}x - k\frac{dx}{dt} \tag{3}$$

(Re < 1000)

$$\mathrm{m}\frac{d^2x}{dt^2} = -\frac{mg}{L}x - k(\frac{dx}{dt})^2 \tag{4}$$

(Re > 1000)

For simplicity, we obtain x using this equation (3),

$$x = Ce^{-\frac{k}{2m}t} t\cos\left(t\sqrt{\frac{l}{g} - \left(\frac{k}{2m}\right)^2} + \beta\right) \tag{5}$$

Here, $e^{-\frac{k}{2m}t}$ represents an amplitude decay of pendulum, which indicates that the pendulum motion decays quickly as air resistance is larger and mass is lighter. Therefore, Kinetic energy of iMS-100's pendulum motion can decay quickly compared with those of conventional radiosondes (Fig. 5).

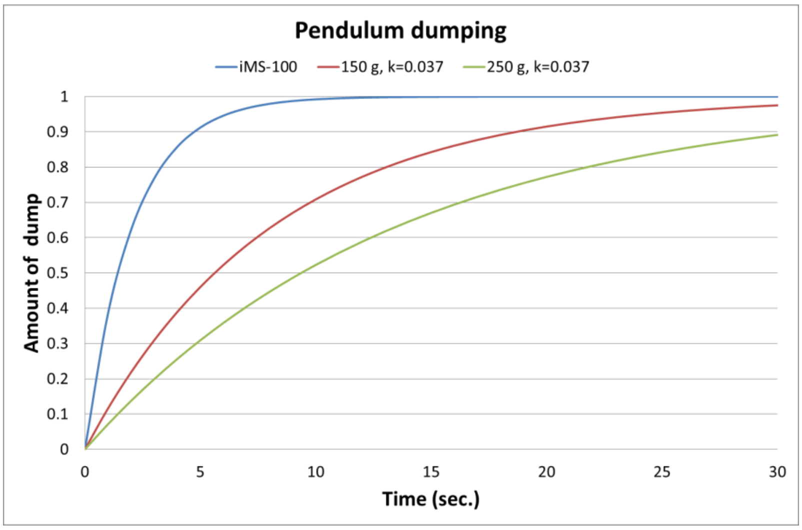

Figure 6: Amplitude decay of radiosonde pendulum motion

Figure 6 shows the zonal components of the wind velocity when iMS-100 and iMS-100 with 200 g-weight (approx. 250 g sonde) are simultaneously launched with respective 600 g balloons and 30 m suspensions. In terms of wind raw data, the amplitude variations of iMS-100 are smaller than that of 250 g sonde. The raw wind data of iMS-100 shows within ±3 m/s of its own filtering data. Furthermore, iMS-100 can better capture fine structure of wind compared with 250 g sonde such as up to 2 km above surface and especially can demonstrate the sharp change of wind speed at 3 km and 4.5 km altitude where the magnitude of wind shear is large.

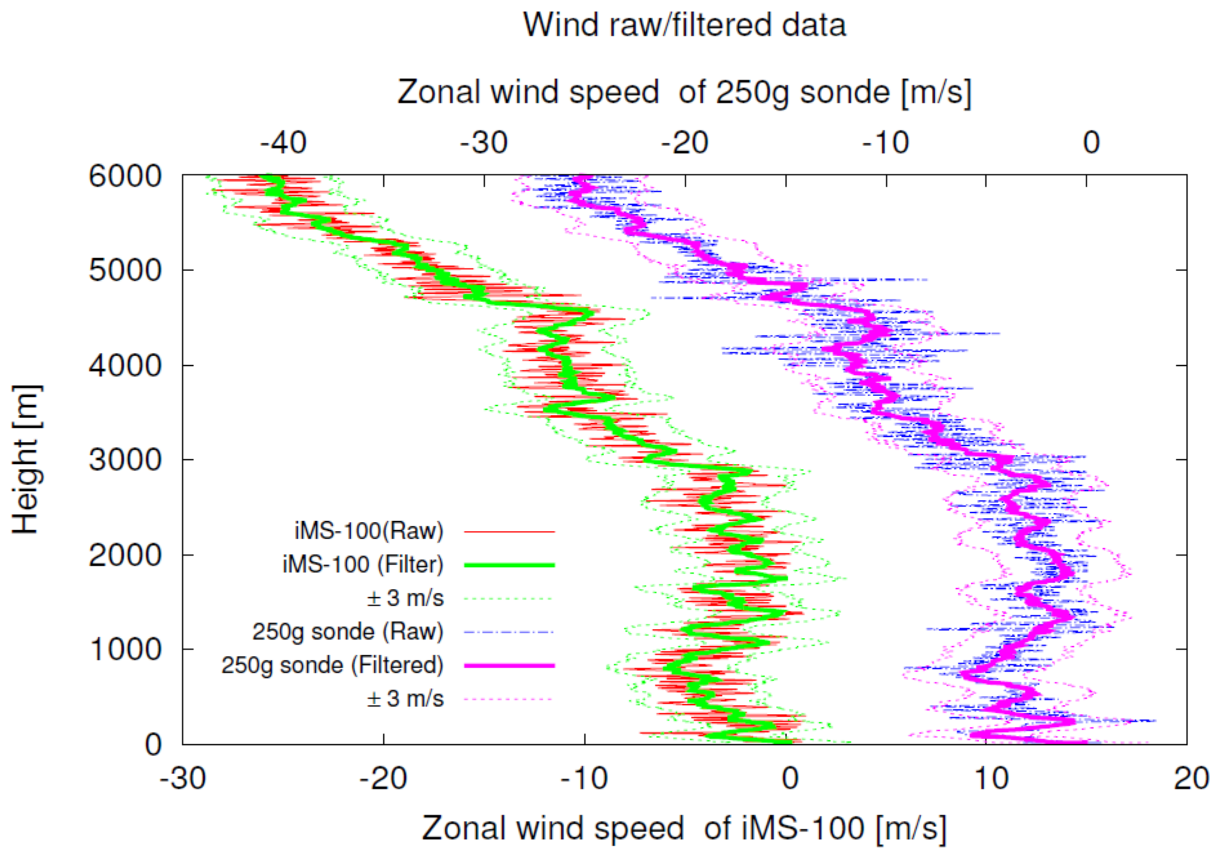

Figure 5: The zonal components of the wind velocity when iMS-100 and iMS-100 with 200 g-weight (approx. 250 g sonde) are simultaneously launched with respective 600 g balloons and 30 m suspensions.

4.2 Temperature

4.2.1 Shape of package

For precise temperature measurement at upper air level, it has been found that not only the solar radiation correction, but also thermal contamination of the sonde package, and directivity of the sensor are highly influential (refer to Shimizu and Hasebe, 2010). The sensor's directivity and thermal contamination appear as a temperature spike. Although these problems can be removed by various filtering techniques, ideally, low directional round sensor, which place at a position less affected by the contamination, should be used.

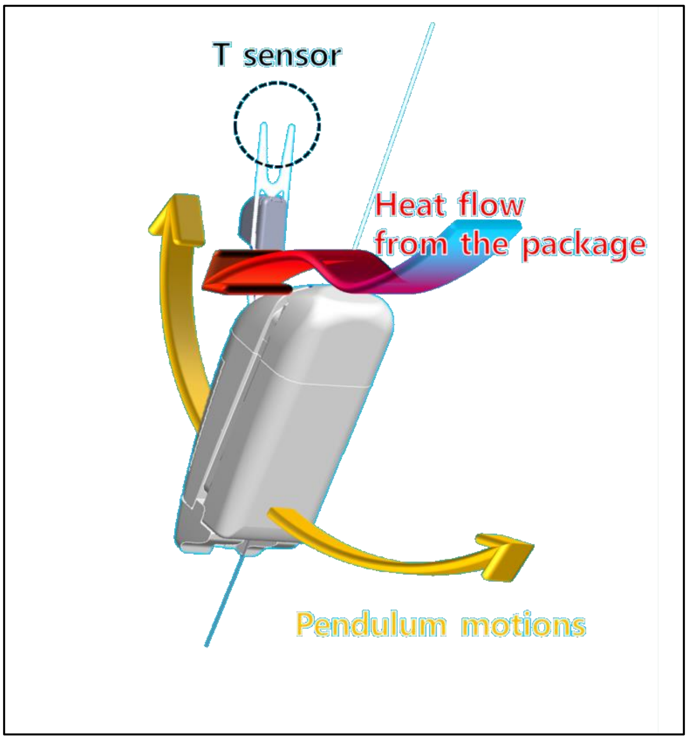

Figure 7: Design concept to decrease heat flux from package box.

iMS-100 is designed to decrease affection to the sensor from the heated ambient air (Fig. 7) by incorporating the following approaches;

* Miniature sonde package reducing the heat contamination
* Small pendulum motions improve angle of attack during ascension, hence the sensor faces less contaminated air.

4.2.2 Flight test

iMS-100 applies the same thermistor as that of RS-06G. But by reviewing the mounting methods and the package design, occurence of temperature spike has been considerably decreased. Figure 8 shows a comparison of raw data during concurrent launch of RS-06G and iMS-100 with respective balloons.

The temperature measurement of RS-06G shows temperature spike due to the influences of the package design, while iMS-100 shows only subtle variations. Thus, iMS-100 can measure accurate temperature without filtering methods as introduced by Dirksen et al. (2013), which enables to prevent decrease in temporal resolution based on filtering window.

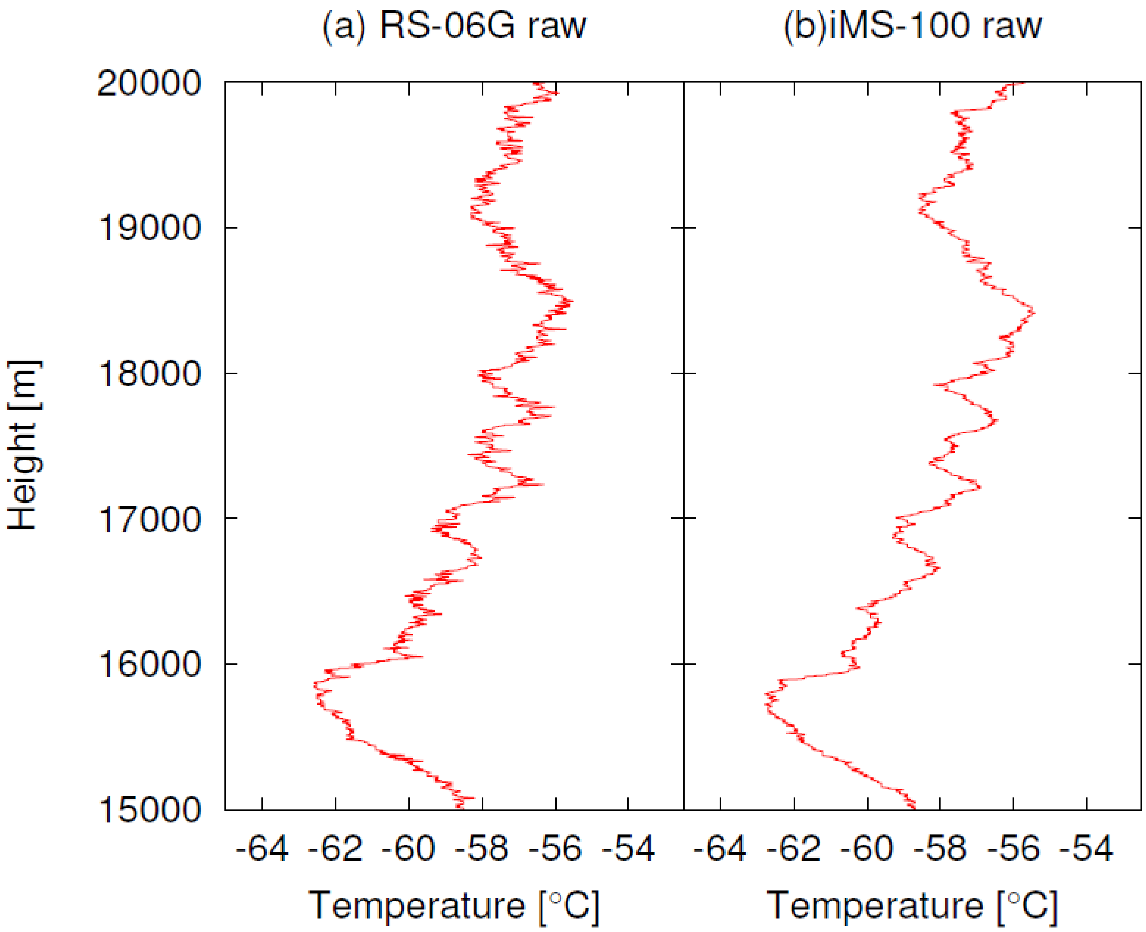

Figure 8 : Comparison of raw temperature data during concurrent launch of RS-06G and iMS-100 with respective balloons at Moriya, Japan.

4.3 Humidity

Current radiosonde generally adapts a polymer humidity sensor, which time constant delays in low temperature condition. Therefore, humidity measurement is difficult in high altitude. Miloshevich et al. (2004) demonstrated that radiation correlation and time-lag filtering can allow the measurement of humidity with the polymer sensor even in low temperature level. In WMO Intercomparison, such similar errors are confirmed in terms of RS-06G humidity sensor (refer to Nash et al., 2011). Sugidachi and Fujiwara (2013) describes in detail to solve these issues on RS-06G. In response to these papers, iMS-100 applies the following improvements.

* Newly developed temperature sensor chip is embedded to the humidity sensor, which can directly measure the heating of sun radiation and the heat capacity-dependent temperature delay.

* Improved polymer film allows accurate humidity measurement even in lower environment.

4.3.1 Laboratory test

Evaluation of time constant with newly developed humidity sensor is shown in Fig. 9. The response time is generally fast when humidity sensor absorbs moisture compared to when it removes moisture. New humidity sensor shows approximately 30% faster response time than that of RS-06G sensor when it absorbs and removes moisture. Table 3 presents the time constant of humidity sensor in various temperature conditions.

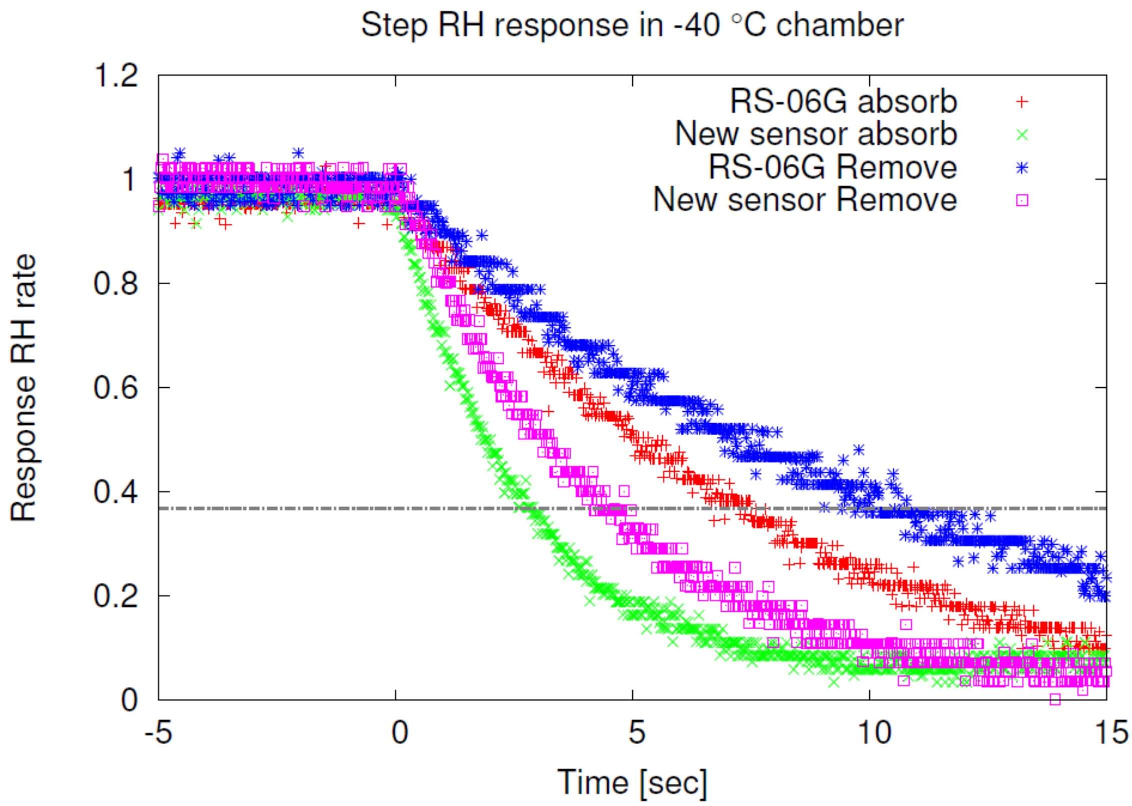

Figure 9: Time constant of new humidity sensor and previous RS-06G in laboratory chamber.

4.3.2 Flight test

Tandem observation of iMS-100 with new humidity sensor and CFH are shown in Fig. 10. This CFH downlink data including the humidity of RS-06G by using interface function of RS-06G. From Fig. 10, it is recognized that iMS-100 performs more accurate measurement in high altitude compared with RS-06G and well coincides with CFH data up to about -70 ℃ (14 km). The continuous evaluation in the lower temperature condition above tropopause height will be planned for more accurate humidity measurement.

Table 3: Time constant of humidity sensor

	iMS-100 Absorb	iMS-100 Remove	RS-06G Absorb	RS-06G Remove
0 °C	0.16 sec (σ= 0.03)	0.16 sec (σ=0.04)	0.50 sec (σ=0.07)	0.78 sec (σ=0.14)
-20 °C	0.47 sec (σ=0.09)	1.05 sec (σ=0.12)	2.58 sec (σ=0.27)	4.81 sec (σ=1.64)
-40 °C	1.85 sec (σ=0.46)	5.14 sec (σ=0.75)	8.51 sec (σ=2.25)	14.66 sec (σ=3.37)
-60 °C	11.03 (σ=2.64)	27.04 sec (σ=5.71)	N/A	N/

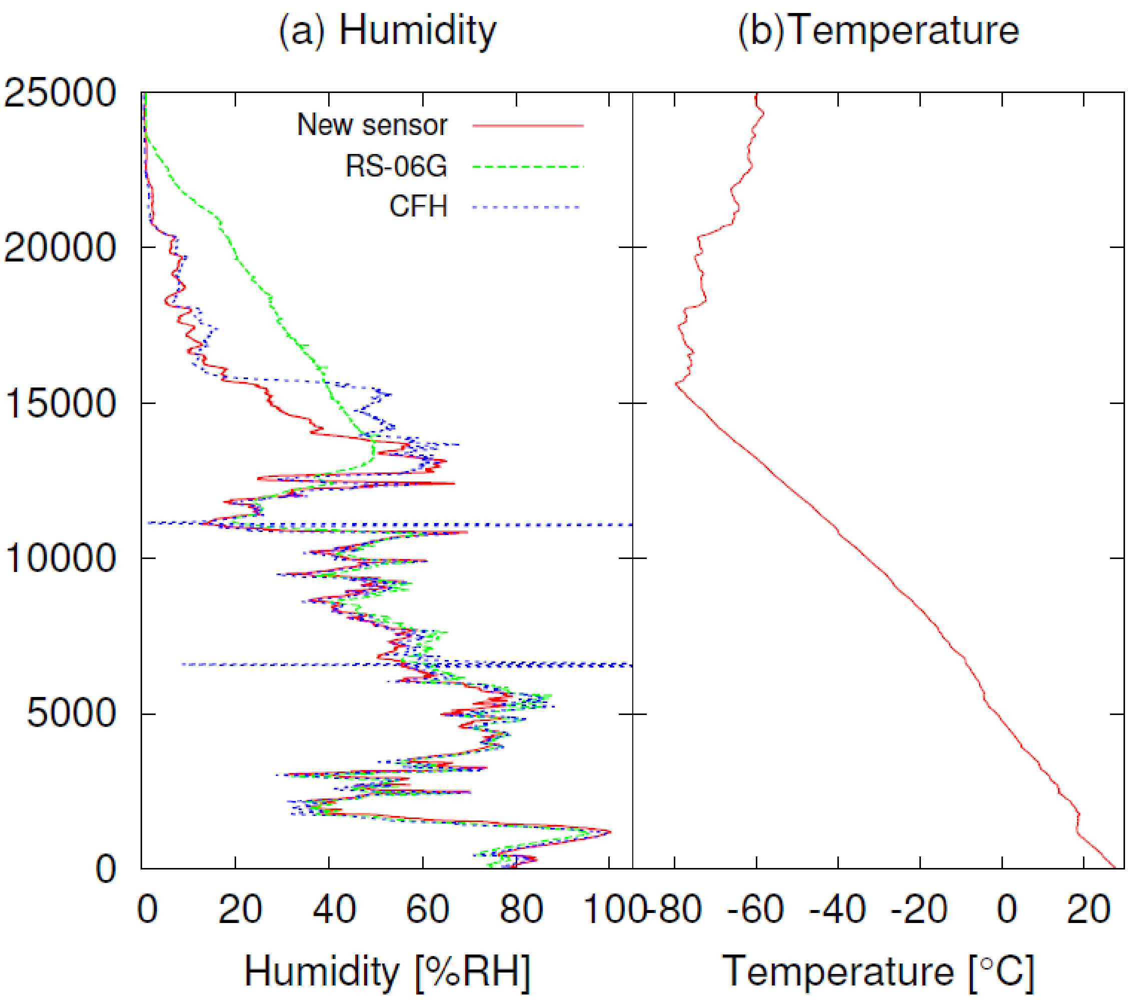

Figure 10: Example humidity and temperature profile of a tropical sounding launched at 18LT in Biak, Indonesia.

5 Summary

I. Meisei newly developed the innovative radiosonde, the world smallest and lightest, iMS-100.

II. Micro iMS-100 allows launch with the smaller balloon and reduce annual gas consumption by ~30% for one station, which significantly contributes to save the total annual operation cost.

III. Downsized radiosonde (iMS-100) reduces the affection from the pendulum motion, which enables to better capture ''in-situ wind motion'' and also helps decreasing error of temperature measurement by reducing adverse thermal contamination from the radiosonde package itself.

IV. The performance of newly developed humidity sensor is quite favorably evaluated at near tropopause and is well coincident with that of CFH compared with previous RS-06G.

For the commercial production, continuous efforts in further quality improvement and evaluation of iMS-100 are implemented.

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