GEOSTATIONARY MICROWAVE SOUNDERS: SCIENCE, APPLICATIONS AND THE GEOSTAR INSTRUMENT CONCEPT

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1. INTRODUCTION

Microwave atmospheric sounders have long provided some of the most important data for use in numerical weather prediction (NWP) and have played an important role in atmospheric weather and climate research. With 7 US satellites now carrying such sensors, we are in a "golden age" of microwave remote sensing of the atmosphere. However, as this fleet ages and is replaced by a smaller number of new sensors in the coming years, the main shortcoming of sensors in low Earth orbit – i.e. poor spacial and temporal coverage and sampling – will become more apparent. Placing such sensors on geostationary satellites, enabling time-continuous views of large portions of the Earth disc, would solve this problem. But the GEO orbit is approximately 40 times higher than a typical LEO orbit, which requires antenna apertures also about 40 times larger than for LEO systems to maintain spatial resolution, and it has not been feasible to develop such systems. Recently, a solution to this problem has appeared in the form of aperture synthesis [1, 2].

2. WHY MICROWAVE?

Microwave sounders have been operated by NOAA on its Polar-orbiting Operational Satellite System since the late 1970's. As numerical weather prediction evolved and satellite data began to be assimilated into forecast models, these sounders became one of the most important sources of satellite data. An infrared sounder has always been paired with the microwave sounder, but it has not had the same impact. This is largely due to the effect of clouds, which are partially transparent in the microwave spectrum but largely opaque in infrared. Assimilation systems have therefore rejected IR data affected by clouds. Considering that less than 10% of the Earth is cloudfree at the relevant spatial resolution, this eliminates most of the data, which in turn results in low information content and low forecast impact.

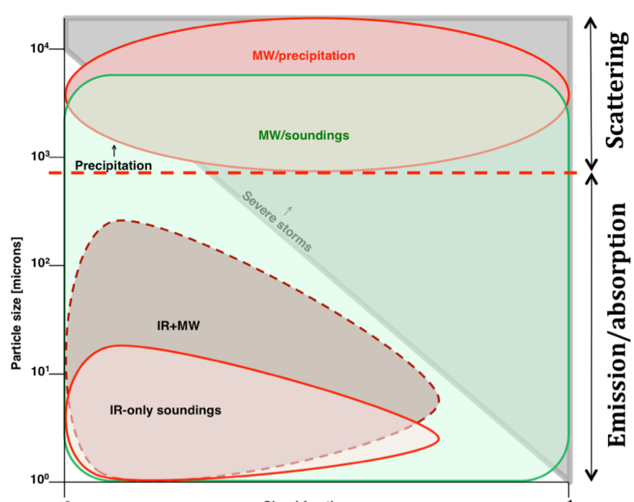

Figure 1. Sounders and cloud regimes

In contrast, microwave observations of cloudy non-precipitating scenes are more easily assimilated, and most of the information content is intact, which results in large forecast impact. Figure 1 illustrates this conceptually. The horizontal axis indicates cloudiness in a scene (cloud fraction), and the vertical axis indicates the size of the cloud particles. The lower left region of this diagram represents “good weather”, and the upper right represents “bad weather”.

In recent years, hyperspectral infrared sounders have become a mainstay in both NWP and atmsospheric research, and it may appear that microwave sounders are no longer needed – but that is far from the truth. As Figure 1 attempts to show, there are cloud regimes that cannot be addressed with IR sounders, i.e. there is a sampling problem. In NWP, the most recent studies show that the microwave sounders still give the most impact of all the satellite sensors, as illustrated in Figure 2. Such studies also show that as more microwave data are being assimilated, the forecast impact grows. This suggests that full and continuous coverage, such as with a geostationary sounder, will yield even better results. Simulation experiments are under way to verify this.

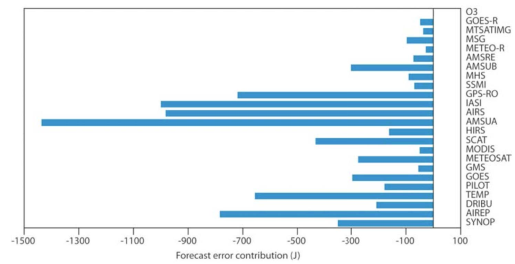

Figure 2. Forecast impact [3]

3. THE CURRENT STATE OF THE ART IN MICROWAVE SOUNDING

The state of the art is represented by the Advanced Microwave Sounding Unit (AMSU), which is now operating on 5 NOAA satellites, 1 Eumetsat satellite and 1 NASA satellite. The AMSU-A unit has 12 channels for measuring vertical temperature profiles from the surface to 1 mb at a spatial resolution of 50 km at nadir and 5 of those to resolve the troposphere – see Figure 3 – while the AMSU-B unit has 5 channels for measurning vertical water vapor profiles in the troposphere (to about 300 mb) at a spatial resolution of 15 km. Vertical resolution of the profiles is 2-4 km. It is also possible to derive surface temperature, cloud liquid water content, and rain rate from the combined units. AMSU will soon be replaced by a slightly more advanced sensor, but it will still represent state-of-the-art capabilities for the forseeable future, even as the underlying technology is advancing.

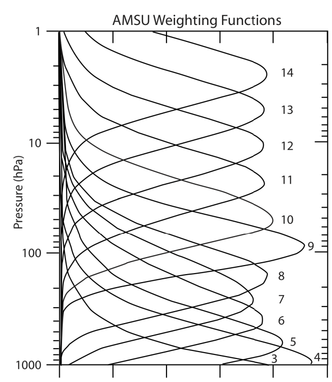

Figure 3. AMSU-A “weighting functions”

4. THE GEOSTAR CONCEPT

The aperture synthesis concept that GeoSTAR is based on was developed in the US [4] and Europe [5]. GeoSTAR is similar to the Microwave Imaging Radiometer by Aperture Synthesis (MIRAS) developed by ESA for the Soil Moisture and Ocean Salinity (SMOS) mission, but with the important distinction that MIRAS operates at 1.4 GHz while GeoSTAR operates at 50 GHz and up. The frequency ratio is close to the ratio between

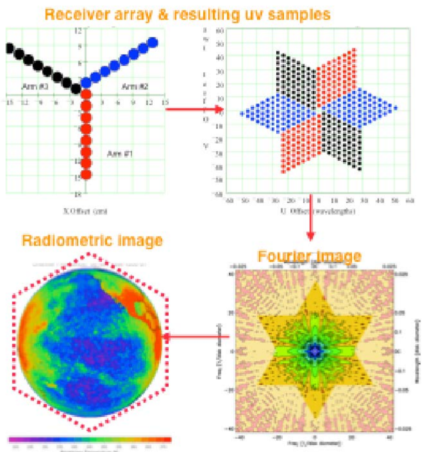

Figure 4. The STAR concept

the LEO/GEO orbit altitudes, and it was the realization that there is a scaling similarity that made it clear that the MIRAS concept can be used for GeoSTAR. Figure 4 illustrates the concept. The upper-left figure is a depiction of the sparse array of receivers, the upper-right figure shows the resulting sampling points in Fourier space (the so-called uv-plane), the lower-right figure shows the Fourier transform of the Earth brightness temperature image in the lower-left, with the sampling pattern overlaid. The system is a spatial interferometer. The direct measurements consist of "visibilities", which are essentially the coefficients of a 2-dimensional Fourier series (lower-right). These are sent to the ground, where an inverse Fourier transform is used to reconstruct the brightness temperature image. This is done for each spectral channel, and the plan is to implement the AMSU tropospheric channels. The system will be built large enough to yield a spatial resolution of 50 km at 50 GHz – the same as for AMSU. Thus, GeoSTAR will have the same functionality and performance as AMSU but with the crucial difference of giving time-continuous observations, with a refresh period of less than 30 minutes. The technology required to achieve this performance has been under development at the Jet Propulsion Laboratory since 2003, and it is now sufficiently mature that a space mission can be initiated by 2012.

5. THE NRC DECADAL SURVEY AND THE PATH MISSION

In 2007 the National Research Council (NRC), an arm of the US National Academy of Sciences, reommended that NASA develop 15 space missions in the coming decade, to replace and enhance the current rapidly aging fleet of earth satellites [6]. Among those was the Precipitation and All-weather Temperature and Humidity (PATH) mission, which will place a microwave sounder in geostationary orbit. The report identified a "MW array spectrometer" as the recommended payload. GeoSTAR is one such concept – the only one being developed in the US – and will therefore likely be the PATH payload. The primary objective of PATH, according to the NRC, is to provide continuous soundings and precipitation measurements under both clear and cloudy conditions, with very rapid refresh rates (15-30 minutes). These observations will be used to improve and constrain atmospheric models, which is expected to lead to significant improvements in storm forecasts as well as improved understanding of atmospheric processes related to the hydrologic cycle. Table 1 lists the most important

Weather forecasting	All-weather soundings, in cloudy and stormy scenes Soundings @<50/25 km every 15-30 minutes (continuous) Synoptic rapid-update soundings Forecast error detection; 4DVAR applications
Hurricane & severe-storm diagnostics	Location, intensity & vertical structure of deep convection NRT atmospheric instability; tornado precursor detection Intensification/weakening in NRT, frequently sampled Measure all H_2O phases: vapor, liquid, ice, rain/snow Operational analysis, forecast verification Improved model microphysics
Rain	Full hemisphere @ $\leq$ 25 km every 15 minutes Directly measure storm and diurnal total rainfall: predict flooding events Snowfall, light rain, intense convective precipitation
Tropospheric wind profiling	1000-300 mb; very high temp.res.; in & below clouds Air quality applications (pollution transport)
Climate research	Stable & continuous MW observations Long term trends in T & q and storm statistics Fully resolved diurnal cycle ENSO; monsoon; tropical moisture flow into the US "Science continuity": GeoSTAR ≈ AMSU

Table 1. PATH applications

PATH applications. The PATH mission can be viewed as a mission to monitor the hydrologic cycle [8].

6. A DEMONSTRATION MISSION IN THE NEAR FUTURE

The NRC placed PATH in the third tier of recommended missions, due to a perception that some time would be requried to develop the necessary technology. Although the GeoSTAR technology is now at least as mature as for second-tier missions, NASA is in the process of systematically implementing the first-tier missions, followed by second-tier missions, and finally third-tier missions. But due to budget limitations, it is unlikely that PATH, as a third-tier mission, will be implemented in the foreseeable future, nor will NASA consider changing the order of implementation. However, there is still a good chance that a US geostationary sounder will be implemented in the near future, for example under the new Ventures program. Thus, a low-cost mission is now under consideration. It will be based on the GeoSTAR concept and have a limited science objective of observing hurricanes and severe storms. With a newly developed method of deriving vertical profiles of reflectivity from microwave sounders, i.e. equivalent to radar observations but at a lower spatial resolution, such a mission will enable powerful new applications related to convective processes and severe storms. Figure 5 shows an example – reflectivity at 6 km derived from AMSU observations of Supertyphoon Pongsona in 2002. With GeoSTAR it will be possible to generate such images continuously and thus cover the entire life cycle of such storms.

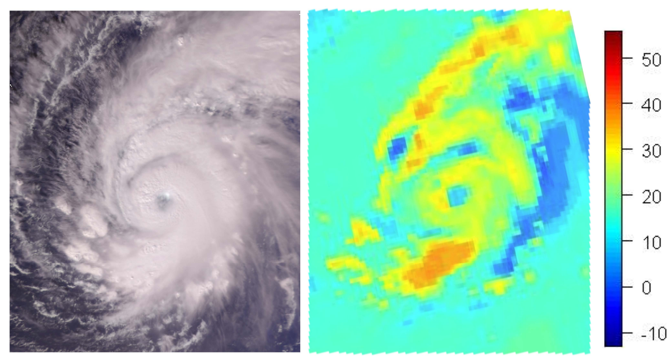

Figure 5. Reflectivity example

7. REFERENCES

[1] B. Lambrigtsen, "GEO/SAMS—The geostationary synthetic aperture microwave sounder," *Proc. IGARSS'00*, vol. 7, pp. 2984-2987, 2000

[2] B. Lambrigtsen et al., "GeoSTAR—A microwave sounder for geostationary satellites," *Proc. IGARSS'04*, vol. 2, pp. 777-780, 2004

[3] C. Cardinali, "Forecast sensitivity to observation (FSO) as a diagnostic tool," *ECMWF Tech. Memo* #599, 2009

[4] C. Ruf et al., "Interferometric synthetic aperture microwave radiometry for the remote sensing of the Earth," *IEEE Trans. Geosci. Remote Sens.*, vol. 26, pp. 597-611, 1988

[5] M. Martin-Neira and J. Goutoule, "A two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations," *ESA Bull.* No. 92, pp. 95-104, 1997

[6] R. Anthes and B. Moore (eds.), *"Earth science and applications from space—National imperatives for the next decade and beyond,"* National Academies, Washington, DC, 2007

[7] B. Lambrigtsen et al., "Monitoring the hydrologic cycle with the PATH mission," *Proc. IEEE*, vol. 98, pp. 862-877, 2010