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WEATHER PREDICTION**

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DISCUSSION OF LONG-RANGE WEATHER PREDICTION

Gregory H. Canavan

A group of scientists at Los Alamos have held a series of discussions over the last few weeks of the issues in and prospects for improvements in "Long-range Weather Predictions Enabled by Probing of the Atmosphere at High Space-Time Resolution," as outlined by E. Teller and others in UCRL-JC-131601. The group contained the requisite skills for a full evaluation, although this memo presents only an informal discussion of the main technical issues. Participants in the final discussion were Joe Duke, MST-7, Howard Hanson, EES-8, John Moses, P-21, Bob Quick, CST-1, Brian Newnam, STC, Fred Mueller, STC, and myself.

The group discussed all aspects of the proposal, which are grouped below into the headings: 1. Predictability, 2. Sensors and satellites, 3. DIAL and atmospheric sensing, 4. Localized transponders, 5. Summary and Integration.

Briefly, the group agreed that the relative paucity of observations of the state of the atmosphere severely inhibits the accuracy of weather forecasts, and any program that leads to a more dense and uniform observational network is welcome. As shown in "Long-range Weather Predictions," the pay-back of accurate long-range forecasts should more than justify the expenditure associated with improved observations and forecast models required. The essential step is to show that the needed technologies are available for field test and space qualification.

Predictability has not been demonstrated, but numerical model experiments indicate that the two week predictions of interest are possible, given adequate and accurate initial conditions. The calculations needed would not stress the computer capability projected to come on line in the same time frame, although it will be necessary to avoid conflicts.

The Satellite buses required are not stressing; they can evolve from existing designs and hardware. Developed lasers are appropriate for precise vector wind measurements. The visible and infrared cameras exist. Microwave sensors can be scaled from developed, space qualified versions.

Lasers for DIAL or line probing of atmospheric temperature and water vapor could take development. However, the reduced accuracy and shorter calibration times for weather measurements should make sensors significantly simpler and cheaper than those for climate. Multiple observations of transponders should permit inversion of column measurements and hence the accurate estimates of local meteorological variables needed.

Materials and fabrication issues for atmospheric Transponders offer a number of options, as do techniques for impressing data on laser beams for readout. The designs for and readout of ocean buoys and distributed land sensors are less developed.

The roughly half dozen major issues that need to be resolved before starting a large scale effort could be resolved in the Laboratory in 2-3 years by about 15 FTE at a cost of about \$4.5M/yr, which is less than a percent of that spent on global change each year.

1. Prediction and computation

Although it is a given that increasing real-time knowledge of the state of the atmosphere will improve initialization of weather forecast models and the forecasts themselves, several issues need to be addressed before the specifics of this proposal are credible from a meteorological perspective. There is a distinction between the theoretical notion of predictability and practical forecast skill. From a given set of initial conditions, fluid mechanical systems magnify initial errors until predictability is lost. The question is how long that takes for weather scales of interest.

There is no experimental evidence that it is possible, even under ideal circumstances, to extend current 3-5 day forecast skills to two weeks, although general circulation model (GCM) experiments over the last few decades have indicated significant correlation for periods as long as 30 days. It is necessary to test whether such predictability, or even two weeks is possible, as forecast skill is judged relative to climatology and persistence. There does not appear to be any way of testing the predictability of the atmosphere short of the observational and theoretical program proposed in "Long-range Weather Predictions." However, in terms of what we think of as Earth's "weather," mid-latitude synoptic systems with spatial scales of a few thousand kilometers (the highs and lows of weather charts)—the 30-day limit mentioned in "Long-range Weather Predictions" is not an unreasonable predictability limit.

For model initialization, there are significant differences between imposing 1-degree temperature or 1 m/s wind errors on scales of hundreds of kilometers, as in current observations and GCM studies, as compared to imposing errors on scales two orders of magnitude smaller. To fully assess the differences, it will also be necessary to improve the representations of physical processes such as clouds in high-resolution as well as to treat new, small-scale instabilities.

The degree to which the proposed system would improve initialization must be quantified, particularly with respect to the steady-state distribution of the transponders. Any increase in observations over the oceans would help weather forecasts, but the cost/benefit analysis depends on how much they would help. Preferential regions for particularly sparse or dense coverage, and quantitative estimates of transponders lifetimes in this context, must be investigated. That can apparently be done by flying Lagrangian particles through existing computed 3-d wind fields, although that could apparently be done more readily at LLNL rather than Los Alamos.

The degree to which it will be necessary to measure and predict the evolution of ocean-surface temperatures is properly raised in "Long-range Weather Predictions," but not fully addressed. The growth or decay of individual weather systems is affected strongly by the

temperature of the water over which they flow. The best known examples are probably tropical storms and hurricanes, in which ocean-surface temperatures can change significantly on the time scale of a week. That requires adequate space and time resolution in ocean and ground measurements and probably some coupling of atmosphere and ocean models.

It is unclear why the proposal seeks initialization observations in the free atmosphere at scales of up to 3 km but is sanguine about 30 km scale observations of winds and temperatures at the surface. Ocean models can require resolution about an order of magnitude greater than atmospheric models to compute the fundamental processes of the flow field. The finer scale surface observations available from satellite instruments will be useful in quantifying these effects.

These issues are complex, but can be addressed readily with careful numerical experiments with global, regional, and small scale atmospheric models available at LLNL and LANL with a relatively small investment in new resources, personnel, and computer time. Computability is not an issue, although it would be necessary to avoid duplication in and conflicts over priorities and personnel for ASCI efforts on climate research. This would involve a small fraction of the funds spent on climate change, in which NOAA is over committed to support current measurements with sparse, expensive nets, and the NSF is still spending much of its research budget on a large number of low-resolution GCMs, which do not impact this area.

2. Sensors and satellites

Satellites are the preferred way to probe the atmosphere and read out ocean and land sensors in real time. There are not any major issues on the satellite bus or communication system. LLNL has noted that Los Alamos has significant capability in those areas, which could be uniquely valuable to the effort, and connections to the Air Force Space Command, which would probably control the constellation and ground the data just for secondary benefit to the DoD.

The Lidar adapted from Brilliant Eyes, Pebbles, and Clementine are about ideal for the vector wind measurement with retro-reflectors, and already space qualified. There does not appear to be any need for further technology development in that area. It is not clear that the visible-infrared sensors carried over are appropriate for atmospheric probing and ocean and surface measurements.

It should be noted, however, that these space sensors for atmospheric observation have a significant advantage over the NOAA and NASA sensors for climate change, which require ~ 0.1 degree calibration over times scales of decades. By contrast, the "Long-range Weather Predictions" ~ 1 degree requirement over a few weeks could easily be satisfied by any of the sensors discussed—provided they are measuring the right variables. That is the main reason the satellites could be relatively simple, cheap, and numerous.

A number of variables and the sensors needed to measure them are not addressed. The visible and infrared sensors and lasers cannot see through thick clouds; thus, there would be no

way they could measure the conditions below clouds or the rainfall from them. The logical way to do that would be to put a microwave sensor on each satellite with which it could perform complementary measurements. A microwave AMSU sounder would be a logical adjunct to the lidar measurement in any case. The appropriate microwave sensor for clouds and precipitation would be a scaled down version of the TRIMM developed for tropical rainfall. Flown at the proposed 400 km rather than the current 780 km altitude, it should be reduced in weight in cost by factors of about four, which would let them fit within the rough mass budget. It should be possible to re-engineer them for this application on the time-scales indicated. They would, however, only provide resolutions of several tens of kilometers, which would not meet all objectives discussed above.

It would also be desirable to add a microwave sensor to measure ocean surface wind and transport. The logical sensor is a scaled down version of NASA's Scatterometer, which would also fit on the platform. Sensors for the measurement of cloud bottom land surface wetness would also be extremely useful to the DoD weather services. The former could evolve from TRMM; the latter from single purpose microwave sensors.

3. DIAL and atmospheric sensing

While the proposed for vector wind measurements seems adequate, more work is needed on sensors for the remote measurement of temperature and water vapor. Specifically, it is necessary to determine whether it is possible to achieve the 2 week requirement of $\Delta T \sim 1$ degree locally with a combination of DIAL and spatial inversion using the measurements from adjacent transponders. An assessment of LLNL's advanced laser measurement would also be useful. An overall assessment is given here. Appendix A gives more details and references.

In principle, it should be feasible to use the micro-balloon return signals to obtain some measure of the atmospheric water vapor and temperature. Each micro-balloon has associated with it a round-trip integrated path absorption between it and the satellite.

The laser system requirements are substantially different than those for wind measurement. For water vapor measurements, a wavelength tunable laser capable of generating many narrow line width ($< 0.1/\text{cm} = 3 \text{ GHz}$) lines is required. By comparing the return signal from each balloon at different wavelengths, a measure of the total integrated path absorption is obtained for each balloon in the laser footprint. The question is how, and with what kind of accuracy & spatial resolution, can many such integrated path measurements be inverted to give the desired vertical distribution of water vapor concentration?

Molecular absorption cross-sections and line widths are pressure and temperature dependent, so this inversion this is somewhat like a computer aided tomography (CAT) scan inversion. This question alone could be a suitable research topic for the future. Candidate laser systems for this measurement include Ti:Sapphire, Cr:LiSAF, Alexandrite, and others.

For temperature measurements, DIAL absorption in the Oxygen bands around 760 nm has been discussed in the literature and demonstrated experimentally, as a viable way of determining the temperature. Again, the details as to the viability of inverting integrated path absorption data to get local temperature must be investigated. Because DIAL techniques rely on spectrally narrow absorption features ($\sim 0.1 \text{ cm}^{-1}$ near the ground—narrower at altitude) and the orbiting platform is moving at $\sim 7 \text{ km/s}$, which produces a Doppler shift of $\sim 0.43 \text{ cm}^{-1} = 13 \text{ GHz}$, laser wavelength control becomes a stringent requirement.

4. Localized transponders for Long Range Weather Predictions

Ten centimeter diameter balloons made from mylar with a fluorinated polymer overcoat have been suggested as long duration micro-transponder. Balloons currently used in high altitude experiments are of two types: zero- or constant-pressure. Zero-pressure balloons are relatively easy to fabricate and are usually composed of only a polyethylene or mylar fabric about $20 \mu\text{m}$ in thickness. However, their lifetime is only a few days to a week. Constant-pressure balloons would have an extended lifetime, perhaps a few hundred days, for large balloons. These materials are composite materials and of greater thickness to accommodate increased mechanical stresses and permeability problems. This type of balloon would be appropriate for micro-transponders, providing the thickness of the composite material could be reduced significantly to a total thickness $\sim 1 \mu\text{m}$.

The constant pressure balloon is made from a composite material consisting of layers of molar, polyethylene, nylon, ripstop fabric, and adhesives. Each layer fills a different role: the polyethylene and mylar in these composites are responsible for the permeation barrier; the scrim or ripstop fabric is responsible for the high strength to weight and fracture toughness of the composite; the nylon provides some substrate stiffness; while the adhesive bonds the components and improves pinholing resistance.

The fill gas chosen for micro-transponders is a hydrogen / nitrogen mixture. For a slightly overfilled balloon (1.1 times the atmospheric pressure) 10 cm in diameter, the composition would need to be 100% hydrogen to enable the skin to approach $1 \mu\text{m}$ in thickness and be neutrally buoyant at 20 km. A 50:50 mixture of the two gases would decrease the thickness to approximately $0.5 \mu\text{m}$. The lifetime of a balloon with these dimensions would no doubt decrease with respect to that of a larger balloon for two reasons: as the diameter of the balloon decreases its surface area to volume increases; and the thickness decreases. The wall permeability increases for both cases; the hydrogen gas leaks out at a much higher rate. The use of helium as an alternative gas would decrease permeability, which would lower the required wall thickness.

Some work on decreasing the permeability of thin films using very thin coatings (a few hundred angstroms) of aluminum, glass or diamond like carbon has been presented in the

literature. This technique would need to be applied to the micro-transponder wall material to increase the balloons lifetime. It is a commercially viable technique and is used extensively in the food packaging industry. It has not, yet, been attempted on such a thin walled composite material. Wall permeability is not a show-stopper, just an area to focus on for a practical transponder.

Commercial sources for less than 0.5 μm mylar and polyethylene can be found, and fabrication of a composite film with these materials seems possible, including the hydrogen barrier coating. These new materials would need to be developed, characterized thoroughly, and a bonding method would need to be explored in order to create the micro-transponders. The fabrication of a prototype balloon could then be accomplished and details of its survivability used to iterate the design of the final micro-transponder.

Los Alamos MST-7 has extensive experience in polymer synthesis, processing, and characterization. It also has significant experience with various coatings activities including chemical vapor deposition and physical vapor deposition. All would be needed to fabricate prototype micro-transponders. We are also active in the area of hydrogen membranes and separations. Currently we have cooperative research agreements with several industrial partners including DOW, Ford Motor Co., BF Goodrich, and PPG. These interactions should facilitate the development of such a composite material and the final micro-transponder balloon.

The temperature sensing element can be a thin film 100-200 nano-meters in thickness. We envisage that the load-bearing member as shown in "Long-Range Weather Predictions" can itself be coated with a barrier material such as a thin layer of aluminum or gold. On the top of barrier, the perovskite film can be deposited by plasma spray or a variety of other techniques, although we would need to carry out some tests. Since the thermal expansivity of the perovskite temperature sensing material and the load-bearing material have different thermal expansivities, the intermediate layer will smooth out the interface. The same idea also holds since the hardness of the perovskite material is similar to mild steel. The buffer layer makes a system with more "give". Since the transponder will be cycled every day, one wants to prevent tribulation effects as much as possible. It will be possible to load the retroreflective elements on the same load bearing member.

It should be possible to manufacture within the DOE labs a sufficient number of transponders to carry out tests in the atmosphere up to 20 km possibly over a site such as Los Alamos, Livermore or White Sands. Initially, most of the research and development will be carried out in a bench-top environment, but one will want to move toward tests on actual floating transponders in the second phase of this project following a standard pattern of proof of principle development. Full-scale manufacturing of the transponders for the final system will be carried out with the help of such well-known American firms such as 3M, Boeing, LM or duPont.

5. Summary and Integration

The issues requiring resolution in Prediction and Computation, Satellites and Sensors, DIAL and Atmospheric Sensing, and Localized Transponders are distinct by require integrated solutions. It is not useful to design wind, temperature, or water sensors that could not support the requirements for Prediction or that violated the mass or volume capacity of the Satellites. Thus, integration is needed to keep the various investigations tied to a common design as it shifts in response to additional information.

The nature of the needed integration is illustrated by the choice of lasers for atmospheric temperature and water vapor measurements. While the laser for wind measurement is straightforward, that for temperature and water vapor required significantly greater spectral content and control. Thus, it might be necessary to use a separate laser for each. Or wind might be measured by one and temperature and water vapor by one other laser. Or the DIAL lasers for temperature and water vapor might have enough energy to measure all three. Each option has differing requirements for the Spacecraft, communication, and interpretation as well as for the retro-reflectors, absorbers, and rotators on the transponders—particularly if the laser performs more than one measurement. While this requires Integration, it is a great strength of the concept: there are several approaches to each issue. Indeed, the full suite of measurements could be taken either locally on the transponder or non-locally through Dial with only wind from the transponder.

The main tasks requiring coordination are:

1.) Prediction and Computation	2 FTE/yr
review predictability analyses	
determine required measurements, accuracies	
2.) Satellites & Sensors	3
bus design & interface	
re-scale microwave sensors	
3.) DIAL and Atmospheric Sensing	4
laser studies, tradeoffs, and measurements	
line integral inversion	
4.) Transponders	5
fabrication technology	
magnetic material studies	
5.) Integration	1
cross integration	
experiment design	
Total	15

At current costs that would require about \$4.5M/yr, assuming capital equipment is included.

That is presumably comparable to LLNL's estimates for the remainder of the tasks, as a space qualified sensor package probably costs ~ \$10M and a satellite test ~ \$100M over 2-3 years. More precise costs would require a detailed discussion of tasks and responsibilities.

One concern that has not been addressed above is the issue of environmental impact. This is likely to be viewed by the public as extraordinarily intrusive. There would be about one of these balloons over every medium sized city on earth, which mean that few areas would be free of their impact. Thus, the issue of bio-degradadation or remediation of rained out materials must be given serious thought in the choice of materials and fabrication. Thank you for your attention.

Appendix A. Temperature and Water Vapor Measurement

Water Vapor (Note: this appendix was prepared several years ago, there was not time to update it for this discussion). Most common LIDAR approaches to measurement of the concentration of atmospheric water vapor as a function of altitude are differential absorption (DIAL) and vibrational Raman scattering. Work in this field through 1991 has been reviewed by Grant.^{ref1} Extensive sensitivity analysis using the DIAL approach for airborne and satellite platforms has been described by Ismail et al.^{ref2} At the current level of lidar technological capability, the DIAL method is considered the most viable approach for a satellite application.^{ref1} Clifford et al.^{ref3} have authored a recent review of ground-based remote sensing instrumentation for atmospheric winds, water vapor and temperature profiling that includes LIDAR techniques.

In the case of DIAL, the absorption bands of water around 720 nm have received the most scrutiny although the other bands near 820 nm, 940 nm, 1.14 μm , 1.4 μm , 2.0 μm , and 10 μm are available as well. Much of the analysis at 720 nm carries over to the other wavelength regions. Careful examination of many physical effects is necessary to determine which particular absorption lines are most suitable for determination of the water vapor profile and what measurement accuracy levels can be expected, given the characteristics and limitations of the LIDAR platform under consideration. Multiple lines are most likely required to accurately monitor the different parts of the atmosphere. References 4-9 are a short sample of ground- and airborne-based water vapor DIAL experimental test reports for a variety of wavelength regions. Analyses of actual airborne platform data near 720 nm^{ref4} have shown the DIAL water vapor profile measurements to be within 10% agreement with *in situ* probes under varied atmospheric conditions.

For a satellite platform, the limited amount of time available for interrogation (a few minutes) of a particular region of the atmosphere will be a major driving force in the LIDAR system experimental approach, design, and ultimate measurement accuracy and spatial resolution.

Temperature. A variety of LIDAR approaches are currently under investigation for determination of atmospheric temperature profiles, including Rayleigh, Doppler broadened Rayleigh, rotational Raman, vibrational Raman scattering and DIAL techniques.^{ref10-15} In the upper atmosphere (> 30 km), where the backscatter signal is dominated by molecular scattering (no aerosols), undispersed detection of Rayleigh scattering is being routinely used to measure the atmospheric density. The assumption of hydrostatic behavior allows one to relate atmospheric density to temperature. When aerosols are present, dispersion of the backscattered signal is necessary to separate out the spectrally narrow aerosol component from the Rayleigh component, which is broadened primarily by the Doppler shift associated with a Maxwellian distribution of molecular velocities. A measurement of the Doppler broadened spectrum yields a measure of

temperature directly or the hydrostatic assumption can be invoked from density only measurements. Heavy aerosol loading and extinction effects complicate this approach significantly. Analysis of the rotational Raman bands of N_2 and O_2 can be used to determine temperature below 30 km altitude^{ref11} from temperature induced changes in the Boltzmann rotational state population distribution. Simple two filter designs are currently being developed.^{ref10, ref12} Although precision < 1K has been reported over selected regions of the atmosphere, typically, long integration times (sometimes hours) have been required.

With respect to the DIAL technique, temperature information can be obtained by monitoring temperature induced changes in absorption strength in molecular O_2 ^{ref14} or H_2O ^{ref15} ro-vibrational bands. O_2 absorption is the preferred method because it is uniformly mixed up to high altitudes and its high concentration allows one to work with high rotational energy states where the temperature dependence is highest. If the temperature dependence of the pressure broadened absorption lines is well understood, examination of the absorption lineshape of a single line can yield temperature information. Alternatively, changes in the absorption of two different lines in the same rotational state manifold can be used. Recent work by Theopold et al.^{ref14} has demonstrated DIAL temperature measurements using O_2 absorption around 770 nm with an absolute accuracy on the order of 4 K within the planetary boundary layer, with a vertical resolution of 82 m and 30 min. integration time. The error in temperature gradients was estimated at 0.5 K per 100 m layer. Aerosol particle backscatter and extinction effects can be a major source of noise.

For a satellite platform, the limited amount of time available for interrogation (a few minutes) of a particular region of the atmosphere will be a major driving force in the LIDAR system experimental approach, design, and ultimate measurement accuracy and spatial resolution.

ref1

"Differential Absorption and Raman Lidar for Water Vapor Profile Measurements : a Review" by W. B. Grant, Optical Engineering, v. 30, pp. 40-48, 1991.

ref2

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"Simultaneous Remote Measurements of Atmospheric Temperature and Humidity Using a Continuously Tunable IR Lidar" by M. Endemann and R. L. Byer, Applied Optics, vol. 20, pp. 3211-3217, 1981.

Appendix B. Transponder science

Because of the number of transponders needed for the global system, their individual cost must be kept modest: This implies that only the simplest types of sensors will be appropriate: Passive systems that can be probed optically fit within this context or broad guideline nicely.

The first question is transponder temperature measurement and temperature sensitivity. There are several ways this can be accomplished on a transponder. Quite recently there has been a renewed interest in magnetic perovskite materials based on lanthanum and manganese. By doping these materials with about 30% substitution on the lanthanum sub-site with either calcium or strontium, a material is produced with a substantial temperature alteration of its resistivity. We show in Figure 1a and 1b this effect as a function of temperature.

The doped manganite materials have insulator-metal phase transition, which creates a bell-shape resistive transition curve with the peak temperature (T_p) corresponding to the ferromagnetic transition temperature (T_c). The resistivity of the materials sharply decreases below T_p , which leads to a very high temperature coefficient of resistance. This phenomenon can be utilized for many novel applications. To meet the requirements for different purpose, we can tune the transition temperature of the materials in a wide temperature range by using different dopants, varying the doping concentration, and changing the processing conditions.

As can be seen the calcium based-material shows a logarithmic derivative or $(1/R) (dR/dT)$ of 13.1 % per degree K at 245 K. The strontium-based material is a ferromagnet with a broader temperature phase transition. By combining both Ca and Sr doping, it is highly likely that we can create a tailored material with superior qualities for the present application. It is envisaged that one should use the magneto-optical polar Kerr effect as the primary temperature sensor. This will be better because this effect is less sensitive to fluctuations and scatterings which may. As is well known, this effect measures the conversion of the input linear polarized light to elliptically polarized light upon reflection. The angle of "rotation" is a sensitive measure of the transponder temperature. It should be fairly straightforward to meet a design goal of measuring the temperature with a precision of 1 degree Kelvin over the temperature range of the troposphere and near stratosphere using transponders.