**MOSAiC Flux System Plan**

21 Sept 2017

**1. Overview**

This is a plan to design and implement surface flux measurements for MOSAiC, as part of the overall PSD flux measurement strategy. The specific objectives include developing/implementing a manned flux tower (10-15m) and developing/implementing a network of 3 to 5 quasi-autonomous surface flux stations. The flux tower will be similar to towers that PSD has implemented in the past at numerous locations, including in the Arctic (Eureka, Tiksi, SHEBA), with line power and daily maintenance. The atmospheric surface flux stations (ASFS) will be similar to the Portable Atmospheric Mesonet (PAM) stations that were designed by NCAR for operation at SHEBA. The baseline plan is to simply duplicate the PAM stations, and to build on this baseline design by adding enhanced approaches to instrument rime mitigation, communications, and power production. This document is a living document that will outline a schedule of activities and outline the many components of these systems that must be addressed. Initially many of the sections include the requirements that are needed to meet scientific objectives. Funding for this activity is provided by an NSF grant to CIRES and by support from the PSD Front Office. For the later, the front office has agreed to support engineering for system enhancements. A funding support strategy will be developed to appropriately coordinated PSD federal and CIRES employees. General oversight for implementing this plan will be provided by Rich Lataitis.

**2. Schedule**

Field deployment of all assets will occur in October 2019. It is anticipated that all equipment will need to ship out of Boulder in August 2019. This timeline lays out a schedule to develop the necessary systems and meet the deployment deadline.

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| **Deadline** | **Action** |
|  | Scientific conceptual design: Instrument list and system requirements, conceptual deployment design |
|  | Mitigation strategy: Riming on radiation and sonic equipment |
|  | Communication system design: |
|  | Power system design: |
|  | ASFS structural design: |
|  | Tower design:  |
|  | Procure Tower equipment |
|  | Procure initial ASFS equipment |
| Fall 2018 | ASFS Prototype build |
| Winter 2018-2019 | ASFS Prototype field test (Barrow?, Colorado?) |
|  | Procure final ASFS equipment |
| ?? 2019 | Develop field personnel schedule |
| Spring 2019 | ASFS Duplication / Production |
| Spring 2019 | Software development |
| June-July 2019 | Final test installation: Full tower set up; full ASFS set up |
| July 2019 | Calibration of systems |
| August 2019 | Pack and ship equipment to Tromso, Norway |
| September 2019 | Mobilization in Tromso |
| October 2019 – October 2020 | Field activities |
| October 2020 | Demobilization in Bremerhaven |
| December 2020 | Calibration of systems |

**3. Autonomous Atmospheric Surface Flux System**

Semi-autonomous atmospheric surface flux stations (ASFS) will be deployed at variable distances (~15km) from the Polarstern and in any direction. These stations will be designed to measure all components of the surface energy budget at one level without routine maintenance, and must include strategies for ensuring robust measurements in the extreme conditions that will be encountered (typically ice saturated, temperatures down to ~-45C, etc.). In particular, rime mitigation strategies will be needed for broadband radiometers and sonic anemometer. The stations may be designed to include licors, but these may not be used due to potential difficult operations in the extreme conditions and because the latent heat flux is expected to be small. Additional measurements will include sonic snow depth, IR surface temperature, meteorology and winds at two levels, pressure, and GPS. A camera will be included to monitor/track conditions of the instruments and local region. Onsite data processing will be required to produce first-order quality assurance data. Limited data must be transmitted back to the ship to enable assessment of operations and data quality. The systems will be visited at 1-2 month intervals and must be designed with sufficient power supply to last for up to 2 months. Fuel/power source will be refreshed at these intervals. The systems should be designed for easy maneuverability, including towing with a snow machine and lifting with a helicopter.

**3.1 System Structural Design**

Optimally the ASFS will be designed as a single, transportable unit that can be pulled or lifted with a helicopter or crane (once some external instrumentation has been de-installed). This mobility is important to adjust the deployment relative to evolving ice conditions. This design should consider the option of floatation such that the system might be recoverable under sever ice breakup. [This sub-section will outline the general structural design as it is developed.]

**3.2 Instrument Suite**

The following sub-sections outline the basic approach to each instrument component of the ASFS. Each will outline specific instruments that will be employed and the specific considerations for installation and operation. Where appropriate, each instrument sub-section will include: a detailed plan for addressing environmental challenges; consideration for specific installation; a full assessment of typical and maximum power consumption that will be required; any required calibration including the necessary timing; a full plan for spare equipment and parts that is needed; and other details.

***3.2.1 Radiation suite with rime mitigation strategy***

ASFS radiation will include 4 global radiometers (LWU, LWD, SWU, SWD) mounted at approximately 2 m AGL. Effective rime mitigation at low power consumption is an important consideration, as will be the detection and logic required to optimally apply the mitigation strategy. The D-ICE project will provide insight into the appropriate radiometers and rime mitigation system. Consider calibration plan.

* LW: Based on D-ICE results, there are two options: C/SGR4+CVF4 or the IR20+VU01. All other options do not have great performance with respect to rime management. IR20 has 1.5W of heat internally, while the VU01 uses 6.7W for ventilation. The VU01 can optionally add either 5 or 10W of heat. The C/SGR4 with CVF4 uses 4.1W for ventilation and 6W for heat. For simplicity, we will initially go with the IR20+VU01 but remain open to the SGR4 approach pending the assessment of the IR20.
* SW: Based on D-ICE results, there are multiple viable options: CM11+AWI/Eig ventilator (14.7 W); EKO MS80+ventilator (8.5 W); CM21+Swiss ventilator (10+W); SR30 (2.3W). Of these the SR30 performs just as well as the other systems, other than that it takes a bit longer than some to recover from the “spray” test. With low power consumption the SR30 seems like the obvious choice.
* SW direct/diffuse: We will add an SPN-1 system for operation only in the sunlit months in order to distinguish the direct and diffuse SW radiation, which will provide information on spatial cloud coverage and the SW cloud radiative effect. We will nominally run this without heat to save on power consumption and only use the data when the global measurement is within a reasonable range of our independent SW measurement.

***3.2.2 Sonic anemometer with rime mitigation strategy***

ASFS will include one sonic anemometer installed ~2.5m AGL, slightly above other infrastructure to minimize flow distortion. Metek uSonic-3 Cage MP provides omni-directional measurements and the multi-path measurement technique and have proved to work in a variety of challenging Arctic conditions. Digital communications. The sonic has an option to include an inclinometer, which we intend to include to get the overall inclination of the ASFS. The system has a sensor head heating option. Heating can distinguish between condition control (define T range for heating) and operational control (can define a duty cycle for heating). Heating is on a separate circuit that expects 24 VDC to produce the expected 100W (or 55W). We will plan to apply a lower voltage to get less heating power. First sensors will be available in May.

***3.2.3 Meteorological sensors***

To measure near surface gradients, meteorological parameters (T, RH, winds) are needed at two heights. At ~2.5m AGL the winds could come from the sonic, requiring only T/RH measurements. At 1m AGL full set of T/RH/winds will be installed. Some options for systems include:

* Vaisala WXT530 series sensor packages provide multiple options. WXT534: P, T, RH. WXT536: P, T, RH, Winds, rain. Maximum power consumption is 15 mA at 6 VDC. Heating can be applied at typically 0.4A at 24 VDC. The heater can be turned off as controlled by user specified programs. When heater is on, it is adjusted based on internal temperature reading.
* Vaisala HMT330 series sensor packages provide multiple options. Ola believes these have better RH measurements than the WXT530 sensors. Heater is adjusted based on internal RH reading.

We will go with the HMT337, T/RH sensor installed just below the sonic anemometer at ~2.5m. We will have aspiration capabilities that may only be run in summer when additional power is available. Could install a second level much closer to the surface that has only T.

***3.2.4 Licor***

A Licor system may be used to measure fast response water vapor (and carbon dioxide) at one level just below the sonic. This Licor may be eliminated from the ASFS systems, but the initial target is to plan for operation only during the sunlit seasons with a potential installation in May.

* Licor LI-7500DS is the easiest to install/operate, experience suggests that is stays relatively free of rime.

***3.2.5 Fast pressure sensor***

High-quality pressure measurements are needed to track mesoscale changes and gradients across the observing domain. With anticipated gradients being quite small, the accuracy of standard pressure sensors may not be high enough.

* Paroscientific, Inc., Digiquartz broadband barometer, model 6000-16B-IS with success, with accuracy of 0.08 hPa and resolution of 0.001 hPa. Wilczak uses these.
* Vaisala PTB330 (Class A) with accuracy of 0.1 hPa and resolution of 0.01 hPa. Less accurate, but possibly good enough, and likely much cheaper.

After discussions we have decided to go with the Vaisala system to save on expense. We believe that the accuracy, sensitivity are reasonable enough to accomplish our goals.

***3.2.6 IR surface temperature***

Infrared measurements will be used to obtain an estimate of the surface temperature. There are two basic approaches to these measurements.

* Apogee Precision Infrared Radiometer. Full family of radiometers but SI-400 Series supports digital data output. 1.1 mA quiescent, 6 mA transmitting at 12 VDC. This is a relatively cheap approach.
* KT15: \*\*\*\*. This is a relatively expensive approach. We need to determine if this system can operate robustly (and more accurately) at colder temperatures than the Apogee.

***3.2.7 Snow depth***

Sonic ranging measurements will be used to monitor the snow depth near the ASFS, both for understanding the evolution of the snow and for monitoring the height of our instruments relative to the surface. Campbell Scientific SR50A: “Quiescent mode” takes up to a couple mA at 12 VDC, with active sampling mode taking 250 mA at 12 VDC. Model SR50AH includes heating of up to 3W (but this heating is likely not required). Ranging measurements can be made infrequently; perhaps once per hour. If power needs to be saved, could consider this instrument for elimination. System calibration should be done during each site visit.

***3.2.8 Sub-surface heat flux***

To close the surface energy budget, we require some estimate of the sub-surface heat fluxes. This can be obtained from flux plates, which suffer from solar heating, or from temperature profiles measured by a thermistor string. We will plan to have both of these approaches. Multiple flux plates will be installed near the ice top. A thermistor string will be installed across the atmosphere-ice-ocean system. The bottom of the system will extend beyond the bottom of the sea ice into the ocean by more than the anticipated ice growth (to maintain ocean measurements year round). The top of the system will extend up into the air 0.5-1 m above the ice. Thermistors should be at ~5cm intervals near the ice top/snow and can be ~10cm intervals below. Thermistor strings take lots of channels (4 channels/thermistor) so may need to use a multiplexer.

***3.2.9 Ancillary systems***

A number of other systems are needed to support monitoring, diagnostics, and other core functionality, including: camera system, GPS, IMU, internal temperature sensors.

* Camera: The camera will assist in monitoring the instruments and the overall conditions around an ASFS, via pictures taken at 5-10min intervals. The camera will ideally capture a hemispheric or 360-degree view.
* IMU+GPS: This system is needed to continually track the position of the ASFS including its level and heading; it can be sampled at hourly intervals. The IMU must be of high-enough quality to have minimal instrument drift. After discussions, we believe we can get sufficient accuracy out of a dual-GPS antenna system (which will provide position and heading) and an inclinometer that is included on the sonic anemometer.
* Internal sensors will track the enclosure conditions.

***3.2.10 Data logging and operations system***

Data must be logged from all of the sensors. This will ideally be accomplished via digital means so that the logging can occur directly by a small Linux-based computer system (such as MOXA). This system will be responsible for logging all data streams, local storage of all data, on-site data processing, monitoring power supply and system health, and transferring necessary data via the communication system. It should be able to accept incoming information via the communication system to modify operation of various systems (i.e., via a configuration file).

* We need to have the ability for both digital and analog data logging.
* Consider a Campbell CR1000X if it can do everything we need. Need to understand if the Campbell can deal with a 20Hz sonic sampling rate. Also can it do sufficient onboard processing for averages and other information that we need for system monitoring. Can the Campbell create a file to be sent out at a routine frequency?
* If the Campbell cannot do all of this by itself, then we will us a small computer system (MOXA?) in addition to a smaller Campbell data logger (CR6?).
* The loggers can be set up to work with radio or satellite communications. Byron knows about getting an account/permit for satellite communications via the data logger through NESDIS. We may want to look into this.
* While there are multiple types of data transmission possible, we will use RS485 since this type of communications can combine multiple measurement streams into a single logging stream.
* Nominally 10m cables with all instrument systems. We can shorten these as needed as we will likely include our own connectors to deal with cable management.
* “Subcon” type connectors are good because they are water tight.

**3.3 Communications System**

A minimum level of near real-time communication is required between the ASFS systems and the personnel that are onboard Polarstern. The typical distances will likely be 15-20 km. Ideally we will transfer one file every hour that includes 10 minute statistics (mean, variance) for approximately 30 parameters. At a minimum we will transfer one file per 24 hours that will include hourly statistics for the 30 parameters. In addition to these files, we would like to transfer a low-res photo or two per day. Lastly, we need to have the capability to upload information to the ASFSs, such as a configuration file that would modify how the system operates. This communication could take two pathways: 1) Direct transmission from the ASFSs to Polarstern or 2) transmission via Iridium, which might entail data going to a server in Boulder and then transmitted back via Iridium to Polarstern. The Iridium approach is taken by many other autonomous systems in the Arctic. Sergio said that he has faced some challenges with this in the past. We can consult some of our collaborators at other institutions who do this routinely via the Iridium Rudics service. Alternately, Byron knows about a possibility for satellite-based communication through NOAA NESDIS. For communications directly to the ship we need to consider antennas and the need for omni-directional versus directional antennas and the challenges in operating each of these.

**3.4 Power system**

A stable power system is required to provide the level of power needed to support all instruments, communications, and mitigation strategies for a period extending up to approximately 2 months. It is likely that the stations will be serviced at intervals less than 2 months, but this cannot be guaranteed. Winter is the least certain season as the helicopters used for station servicing face flight restrictions in the dark and at cold temperatures. The power system should include supplies (i.e., fuel) that can be readily transportable via helicopter.

While the full power requirements will have to be determined based on the requirements outlined above, initial plans will aim for 40-100W of power for 2 months of time. This power system can be a combination of batteries, fuel generated power (fuel cells, propane, etc.), and renewables (solar, wind). One possible approach is to have a battery bank of appropriate size, that can be topped off using renewables as possible, with a backup fuel-powered system to top off the batteries when other sources are insufficient. We could also consider the potential of using the warm ocean below.

**3.5 Real-time monitoring**

To enable near real-time monitoring of data and system health will require onboard processing and packaging of information for periodic transfer to operators. This data will include basic parameters for monitoring the health of the ASFS including power system status, power capacity, internal temperatures, position/level, instrument riming status, and photographs. Data statistical summaries will be produced to enable overall data quality assessment. Summary reports should highlight any system that is in alarm status or outside of an expected range. To further enable monitoring of the system health and data quality, a set of routine quicklook plots should be developed to enable quick assessment of the data and comparison with the manned measurements made at the main flux tower near the ship.

**3.6 Operations Plan**

An ASFS Operations Plan will be developed that includes four primary components: 1) Component inventory with component tracking, including spares; 2) Installation plan, to guide basic installation; 3) Protocol for routine monitoring to guide day-to-day operational oversight; 4) Protocol for site visits to guide all maintenance, checks, cleaning, and services to be provided when site visits can be made.

**4. Flux Tower**

A flux tower will be installed on the sea ice within about 500m of the Polarstern. While scientifically it is beneficial to have a taller tower, a shorter tower will be easier to install and maintain on a dynamic ice surface. As a compromise between these two, the main tower height will be approximately 10m, which is acceptable scientifically. The tower will have 3 levels of sonics and T/RH, a licor, delta-T sensors, sub-surface flux plates, sonic snow depth sensors, a camera, and some other supporting equipment. If feasible, a distinct telescoping tower will be used to install a fourth sonic at 20m height. There will be a local data logging system with all data transmitted to local computer systems maintained on Polarstern. Power will be provided via a powerline from Polarstern. The main tower will be designed to allow for daily maintenance of equipment at all levels (climbable). It will also be designed to be moved with relatively limited effort if ice conditions deteriorate.

**4.1 System Structural Design**

Structural requirements for the main tower include: a stable platform to enable all required measurements and their specifications outlined below; the ability for an operator to safely climb the tower on a daily basis (including under challenging weather conditions); ease of access to all instruments for cleaning and maintenance; the ability to readily move the tower if ice conditions deteriorate (i.e., 1-2 days’ time); extra space and mounting positions to accommodate collaborating instruments; consideration for snow/ice ablation near the base of the tower.

**4.2 Instrument Suite**

The following sub-sections outline the basic approach to each instrument component of the flux tower. Each will outline specific instruments that will be employed and the specific considerations for installation and operation. Where appropriate, each instrument sub-section will include: a detailed plan for addressing environmental challenges; consideration for specific installation; a full assessment of typical and maximum power consumption that will be required; any required calibration including the necessary timing; a full plan for spare equipment and parts that is needed; and other details.

***4.2.1 Sonic Anemometers***

The MetTower will include three sonic anemometers installed at nominally 2, 5, and 11 m AGL to measure high resolution variations in 3-dimensional winds. These should be installed in a way to minimize flow distortion. Metek uSonic-3 Cage MP provides omni-directional measurements and the multi-path measurement technique. Digital communications. Sensor head heating will be applied to ensure clean sensors.

***4.2.2 Licor***

A Licor system will be used to measure fast response water vapor (and carbon dioxide) at one level just below the sonic at 5m. We need to explore the options of using an open path (7500) or closed path (7200) system; this will depend on which is best able to deal with riming.

***4.2.3 Meteorological sensors***

To measure near surface gradients and complement the other measurements, meteorological parameters (T, RH) are needed at the three primary heights. Some options for systems include:

* Vaisala WXT530 series sensor packages provide multiple options. WXT534: P, T, RH. WXT536: P, T, RH, Winds, rain. Maximum power consumption is 15 mA at 6 VDC. Heating can be applied at typically 0.4A at 24 VDC.
* Vaisala HMT330 series sensor packages provide multiple options. Ola believes these have better RH measurements than the WXT530 sensors.

***4.2.4 Delta-T sensors***

Delta-T sensors are paired thermocouples that can be installed at two heights to provide an absolute difference between the heights, although not necessarily well calibrated absolute temperature. These will be paired with the basic meteorological sensors to ensure that we accurately measure subtle vertical gradients. Two of these systems will be employed, spanning across levels 1-2 and 1-3.

***4.2.5 Pressure***

High-quality pressure measurements are needed to track mesoscale changes and gradients across the observing domain. With anticipated gradients being quite small, the accuracy of standard pressure sensors is not high enough. Jim Wilczak uses the Paroscientific, Inc., Digiquartz broadband barometer, model 6000-16B-IS with success.

***4.2.6 Snow depth***

Sonic ranging measurements will be used to monitor the snow depth near the tower, both for understanding the evolution of the snow and for monitoring the height of our instruments relative to the surface. Campbell Scientific SR50A: “Quiescent mode” takes up to a couple mA at 12 VDC, with active sampling mode taking 250 mA at 12 VDC. Model SR50AH includes heating of up to 3W. Ranging measurements can be made infrequently; perhaps once per hour. System calibration should be done routinely (weekly).

***4.2.7 IR surface temperature***

Infrared measurements will be used to obtain an estimate of the surface temperature. There are two basic approaches to these measurements.

* Apogee Precision Infrared Radiometer. Full family of radiometers but SI-400 Series supports digital data output. 1.1 mA quiescent, 6 mA transmitting at 12 VDC. This is a relatively cheap approach.
* KT15: \*\*\*\*. This is a relatively expensive approach.

***4.2.8 Sub-surface heat flux***

To close the surface energy budget, we require some estimate of the sub-surface heat fluxes. This can be obtained from flux plates, which suffer from solar heating, or from temperature profiles measured by a thermistor string. We will plan to have both of these approaches. Multiple flux plates will be installed near the ice top. A thermistor string will be constructed and installed across the atmosphere-ice-ocean system. The bottom of the system will extend beyond the bottom of the sea ice into the ocean by more than the anticipated ice growth (to maintain ocean measurements year round). The top of the system will extend up into the air 0.5-1 m above the ice. Thermistors should be at ~5cm intervals near the ice top/snow and can be ~10cm intervals below.

***4.2.9 Optical rain gauge***

It is useful to understand if there is blowing snow in order to interpret the near-surface meteorological and flux measurements. While there will likely be an optical rain gauge operated elsewhere in the primary camp (i.e., by DOE), we will consider operating one at the flux tower.

***4.2.10 Ancillary systems***

Other systems are needed to support monitoring, diagnostics, and other core functionality, including: camera system, GPS, and IMU. The camera will assist in monitoring the instruments and the overall conditions around the tower, via pictures taken at 1-5min intervals. The camera will ideally capture a hemispheric or 360-degree view. The IMU+GPS is needed to continually track the position of the tower including its level and heading; it can be sampled at sub-hourly intervals. The IMU must be of high-enough quality to have minimal instrument drift.

***4.2.11 Data logging system***

Via a local system at the base of the tower, data must be logged from all of the sensors and transmitted to the command center computers. The local data logging system (at tower base) should be robust and require little routine attention, should maintain an onboard data buffer, and should interface with the tower communications system to transfer data to the command center.

**4.3 Communications System**

To minimize the footprint of our activities on the sea ice, the command center will ideally be onboard Polarstern (see Section 5). Thus real-time, wireless transmission of data from the tower data logging system to the command center is required (<1km with line of sight). This system should be able to handle transmission of the full-resolution data streams in near real time. The biggest throughput will be 3-4 different 10-Hz sonic anemometer data sets.

**4.4 Data/Instrument Monitoring**

A daily, data and instrument monitoring plan must be developed. To enable this data monitoring, a suite of routine quicklook plots should be developed to enable easy monitoring of the data and to serve as a means for communicating initial observations to others. This communication will be important for examining specific cases with other scientists onboard Polarstern as well as communicating with PSD scientists and engineers back in Boulder regarding the data quality.

**4.5 Operations Plans**

An set of Flux Tower Operations Plans will be developed that includes four primary components: 1) Component inventory with component tracking, including spares; 2) Installation plan, to guide basic installation of all systems; 3) Zoning document, that maps out the space around the tower and provides guidance on locations that can and cannot be occupied by people and/or equipment; 4) Protocol for routine monitoring and maintenance to guide day-to-day operational oversight, maintenance, checks, cleaning, and services to be provided; this will include a daily checklist; 5) A plan for preventing the adverse effects of snow/ice ablation in the summer season; and 6) a protocol for moving the full tower system if that is needed.

**5. Command Center**

To minimize risk on the ice and maximize the ability to monitor all data streams from the Flux tower and ASFS network, a command center will be established onboard Polarstern. The general plan will be to have a shipping container that is used to ship the Flux tower equipment to Polarstern. Once on-site the tower equipment will be deployed on the ice and this container will then convert into a heated office, workshop, and storage space.

**5.1. Container Design / Requirements**

The command center container must be designed with the following requirements:

* A man-door to enable ease of day-to-day access.
* Anchor points for securing equipment during shipping
* A power system that includes outlets at various locations. This power system will likely require a transformer that can handle typical European power input (240V, 50 Hz) and convert it to typical American power output (120V, 60Hz).
* Shelving for supplies and equipment that is permanently mounted on the walls.
* Workbench and/or table that can be secured to the wall for working on equipment.
* Cable runs mounted from the ceiling for management of cables.
* Cable pass through ports to allow cables to be brought into the container via an insulated interface.
* Antenna’s and mounts for the data communications systems, including communications from the local flux tower and from all ASFS.
* Desks and chairs to accommodate two people.

**5.2 Central Computing**

The central computing system will act as the base of operations for all data streams. It will be connected to the communications systems and all data will be sent from the local flux tower and the ASFS stations to central computing for monitoring and archival. One computer will serve as the primary data management system, including: ingesting all data streams, redundantly archiving all data, producing routine quicklooks of the data. It will have a RAID hard drive system to enable the storage of all data and quicklooks. This system should be made flexible enough to accept data streams from other systems, as our project will likely take on responsibility for daily operations of other instruments. The second computer will serve as an ancillary system for additional processing and onsite work. It will include analysis software for targeted examination of data. It will be the gateway through which all quicklook images are served to the local network for other scientists to access.

A full set of spares will be required, including a full backup computer system, a large collection of spare hard drives for the RAID, multiple USB hard drives for flexible data transportation, spare monitor, spare computer power supplies, spare antennas for the communication system, a full set of spare cables.

**5.3 Data Archival Protocol**

\* Detail plan for data archival.

\* USB hard drives for manual data transport