Milestone: Prediction of atmospheric parameters as a way to support the flexible scheduling scheme foreseen for the ALMA radio interferometer.

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General introduction supporting the milestone:

Astronomical observations to be performed using the ALMA interferometer will be characterized by the observing frequency, angular resolution, the total integration time needed to achieve an expected signal-to-noise ratio, image fidelity, etc. Some of these astronomical observing programs will require good or exceptional atmospheric conditions. In order to make the best use of the given atmospheric conditions, dynamic scheduling will be employed, matching the needs of the observing program to the current conditions. An observing program will be broken down into small observing chunks (so-called source blocks), and might be observed over several days to complete the program's objectives. A granularity of 15 to 30 minutes is being considered for the dynamic scheduling. However, as calibration overhead can easily be 15-30 minutes or more, and with periods of excellent phase stability sometimes being very short, it is easy to see that a knowledge of what the atmospheric stability is likely to do over the coming source blocks (is, 15 minutes to a few hours) could be very useful.

In order to optimize the selection of sources from the observing queue, we would like to be able to predict the phase stability, atmospheric transparency, and wind velocity or their trends on timescales of 15 minutes to 3 hours in advance.

Chajnantor facts:

The efforts to find the best algorithm (model) to provide us with an accurate prediction of the atmospheric parameters (absolute values and trends) have to be adequately supported by the information we already have for the Chajnantor site. We should identify all the Chajnantor facts which could contribute to provide us with a better starting point toward a working prediction model for the atmospheric parameters. The following is only a partial list of the known facts for Chajnantor, enough to support the effort we shall involved in the milestone being described here.

- Chajnantor is located in the southern hemisphere with coordinates: 23°01’10” S, 67°45’10” W.
- Chajnantor geographic altitude: 5050 m above mean sea level.

- Geomorphology: The Chajnantor site is located on the west slopes of the Andes Mountains, and there are no other higher peaks westward all the way to the Pacific Ocean.
- To the north, east, and south, Chajnantor is surrounded by peaks of higher elevation.
- As to the west side, there are some peaks whose maximum elevation is about the average elevation of the Chajnantor plateau. One of these is Cerro Negro with a maximum altitude of about 5050 m, and which is about 9500 m in distance to the west of ALMA interferometer center coordinates.
- Similarly, the Chascón peak is located right to the east of the Chajnantor plateau and its peak is about 8000 m from the center of the ALMA array.
- During 1999, 90% of the time the surface winds were faster than 1.5 m/s (i.e., 90% of the time we could get an accurate determination of the wind direction), the winds were coming from the west (i.e., between 180 and 360 degrees from north through east).
- Of the time the wind was coming from the west, the mean direction is N279W, with standard deviation σ=33.8º.
- The mean wind speed over the period 1995-2002 has been measured to be 6.2 m/s at surface level.
- Wind aloft, from various arguments, are estimated to be in the range 10-15 m/s.
- The windiest months are those from June to September each year. These are also the months with the best stability and transparency conditions.
- There is a clear monsoon weather pattern affecting the area during the summer months of the southern hemisphere with winds slowing and often approaching the site from the east.
- Generally, east winds at Chajnantor are an indicator of bad weather and high opacities.
- The median optical depth measured at 225 GHz in the period 1995-2002 is of 0.062.
- The months from April to November have the lowest 225 GHz optical depth.
- Statistics accumulated in the period 1995-2002 show that during the monsoon months (December-March) the optical depth is five times worse than during the rest of the year.

Working hypothesis:

Prediction of the atmospheric conditions at Chajnantor (phase stability, transparency, wind) with a 15 to 30 minutes lead time could be accomplished by using input data gathered with sounding instruments adequately distributed over the Chajnantor site and its surroundings.

A suitable model for the prediction of the atmospheric conditions at Chajnantor (transparency & phase stability trends) with three hours lead time can be better defined by using a proper mixture of satellite and ground base data.

This working hypothesis is based on some of the known facts for Chajnantor. For instance since the mean wind direction is west (near 279° from north 90% of the time), and considering the Cerro Negro peak is located along the same direction and 9500 m upwind from the center location of the array, implies that monitoring the conditions over the Cerro Negro peak will provide the atmospheric prediction algorithm with valuable data to determine the conditions at Chajnantor at a certain time in the near future. This time depends on the speed with which the moist or turbulent air is moving over the site. For instance with a wind aloft of 12 m/s, this corresponds to a travel time of 792 s. Hence, any atmospheric disturbances coming from the west (the dominant wind direction at the site) will reach Cerro Negro about 13 minutes (in this example) before reaching the ALMA array centre, providing the dynamic scheduling algorithm important information about upcoming conditions.

If fast switching phase compensation is used, phase fluctuations will be the primary limitation in performing high frequency observations. (Not enough is known about radiometric phase compensation to say what will limit observations made with radiometric phase compensation.) Also, phase fluctuations can vary quickly in time, but opacity tends to vary more slowly. Therefore, measurements of the phase fluctuations above Cerro Negro will probably be the most important input for the dynamic scheduling process. While opacity measurements are quite important, it is not clear that opacity measurement above Cerro Negro gives a significant advantage over measuring the opacity above the Chajnantor array centre.

For the 3 hour time scale prediction, we based our hypothesis on the use of satellite images in the infrared band and the real possibility to predict which of the weather image pixels will move over the Chajnantor site at some point in the future. This approach has been studied and analyzed for the operations of the ESO's Very Large Telescope at Paranal and should be considered also as a possible prediction scheme for the ALMA interferometer.

Sounding instruments and data necessary to work the atmospheric prediction model:

- Weather station equipped with sensors with a high accuracy and resolution.
- Radiosonde data gathered over representative seasonal conditions and with time resolution over the day as to infer about the behavior of the local atmosphere conditions.
- Atmospheric phase monitor (ie, radio seeing monitor or site testing interferometer).
- (WVM) Water vapour radiometer (225 GHz radiometer or similar).

Scope:

The goal is to have a working algorithm for the atmospheric predictions by the time ALMA enters into the operations phase (Year 2006).

Intermediate steps toward the verification of the hypothesis stated in this brief document and for achieving the milestone:

Currently, we have no infrastructure at the Cerro Negro site. It is a mountain top some 500 m higher than the surrounding terrain (but the same elevation as the Chajnantor array centre). Furthermore, we have no proof that our concept will work. For example, phase fluctuations could be dominated by local effects. We suggest a cautious approach to exploring Cerro Negro as an atmospheric monitoring outpost.

1) Listing of the Chajnantor facts in order to summarize what we know so far about the site weather and atmospheric conditions.
2) To a first approach we should at least install a complete and automatic weather station at the top of Cerro Negro to provide us with some preliminary information to check our hypothesis. Prior to proceeding with this step, we should prove within certain limits that surface weather data might be a reasonable predictor for the upper atmospheric conditions. From collocated instruments we have seen a reasonable degree of correlation of surface water vapour pressure with the optical depth measured at 225 GHz. However the success of this approach works under certain atmospheric conditions that we do not understand yet well but we think might be associated to the existence or not of a temperature inversion layer above the site. (Note that the correlation of surface measurements and quantities aloft such as opacity is not a prerequisite for monitoring on Cerro Negro to work, but is a prerequisite for the initial step of installing a weather station to provide meaningful data.)
3) To perform simulations of dynamic scheduling to estimate the increase in operational efficiency which can be achieve by monitoring the atmospheric conditions from Cerro Negro.
4) Installation of a weather station at Cerro Negro.
5) Installation of sounding equipment to monitor the atmospheric stability and atmospheric transmission from Cerro Negro.
6) Radiosonde campaign to cover standard weather and atmospheric conditions at Chajnantor over the day and time of year. (Past radiosonde measurements have not adequately sampled nighttime conditions, which often have the best phase stability and lowest wind speeds.)
7) Generation of a working model to predict the atmospheric conditions at Chajnantor.

Cost estimates:
The following table shows the preliminary costs and manpower might be associated with each of the intermediate steps necessary to accomplish the goal set by this milestone.

Item	**Step**	**Description**	**Cost (US$)**	**Manpower (people)**	**Year/QQ**
1	1	Analysis of existing data to summarise our existing knowledge of the weather and atmospheric conditions at Chajnantor.	5000	1	2003/01
2	2	Analysis of existing data to determine weather surface weather data can be use as a predictor of the atmospheric conditions (with focus on atmospheric transparency)	5000	2	2003/02
3	3	Simulations to understand how the efficiency in the operation of the astronomical queue can be improved by having good predictions of the atmospheric conditions in a 30 minutes timescale.	5000	1	2003/01
4	4	Weather Station: includes a CR4 hygrometer for reliable humidity determination, a sonic anemometer, solar flux sensor and lightning protection system.	20000		2003/04
5	4	Field campaign for the installation of a weather station at the peak of Cerro Negro (5 days)	15000	3	2003/04
6	4	Opening an access road to Cerro Negro might be necessary.	25000	Ext. contract	2003/04
7	4	Wireless communication link for Cerro Negro	10000		2003/04
8	6	12 GHz radio seeing monitor (new unit)	50000	2	2004/02
9	6	12 GHz radio seeing monitor (refurbishing of an existing unit and re-installation at the new site)	10000	2	2004/02
10	6	225 GHz room temperature radiometer (new unit)	60000	2	2004/02
11		Field campaign for the installation of atmospheric monitoring equipment (10 days)	15000	3	2004/02
12	5	Radiosonde campaigns (4 per year, 10 days coverage each time)	60000	6	2003 2004
13	7	First generation of a working predicting model			2005/04

Notes:
1: Items 8 and 9 are one or the other.
2: Each step includes a date (year/quarter of that year) we estimate the task should be completed.
3: Field campaigns costs are including the following items: airline tickets, rental of 4WD trucks, lodging, and fuel.
4: The US$5000 estimated as a cost for steps 1,2 and 3 are only to cover eventual airline tickets for collaborators.